Bottle Rocket Handbook

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Acknowledgments

Although I can take credit for being the author of this handbook, much of its content is the hard work of other members, past and present, of the Columbus High School Science Olympiad team. I would like to take this opportunity to thank them and the many others for their contributions to this handbook.

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Introduction

Rocket science doesn't require white lab coats or a job in Cape Canaveral. You don't need a million-dollar budget or a Ph.D. either. An empty soda bottle and an air pump will do just fine, because rocket science is *the theory* behind launching these rockets into the air, no matter whether you are launching a state-of-the-art rocket or an empty soda bottle.

Although pressurized air and water is not quite the same as liquid hydrogen, we still calculate it using the same laws of physics. And it's not as complex as you may think. Typical high school math and physics classes cover 95% of the information needed to understand rocket theory, but few of them take the extra step to apply the basic principles to more complex applications such as rockets.

Science Olympiad offers students the opportunity to explore rocketry and to extend their classroom knowledge to practical applications. This handbook is intended to be a guide to the Science Olympiad event, but it can also provide a useful resource for all types of hobby rockets.

While reading this book, every student (and teacher) has one question in mind: How do I get the longest time aloft? There is no single formula or design to guarantee one- and two-minute launches; the key to making a rocket stay aloft for a minute is to understand *why* the rocket stays aloft for a minute.

Although this handbook contains the "secrets" of building a one-minute rocket, you will not find plans or instructions for

building a winning rocket. However, you will find what I call "building techniques"—these are methods that I and other students at Columbus High have developed. Plans would restrict creativity and ingenuity, and defeat the purpose of the Bottle Rocket event. Techniques, on the other hand, have the opposite effect. By understanding *how* to construct a fin capable of withstanding strong forces and *how* to build a parachute by melting plastic bags will allow you to create any fin or parachute that you can imagine.

Format

This is a handbook—a guide containing lots of various topics related to water rockets. It is not a typical book which you would read cover–to–cover. In fact, the chapters in this book could probably be arranged in any random order, and it would make little difference.

The chapters are definately not arranged in order of difficulty. Do not be discouraged if a chapter seems too long or overly technical. Skip over it and go on to another chapter.

To make the book more organized, the chapters are grouped into three main categories: theory, construction, and mathematics.

The first part, *Rocket Theory*, is the most general and explores the fundamentals of rocketry. Fundamentals often carries a connotation of "basics," but this is not the case in this handbook. By "fundamentals," I am referring to the physics principles which govern rockets and how to apply these principles to building a good rocket. The fundamentals in this book cover topics such as stabiltity and forces, which are overlooked by most other books. These fundamentals are the key to developing a winning design, because they eliminate the guesswork that would otherwise be required. Once you understand the fundamentals, you will be able to look at your rocket, and spot areas for improvement, without using trial–and–error techniques.

Part two, *Rocket Construction*, consists of chapters that each focus on one particular component of the rocket. The building techniques contained in this handbook are ones that we at

Columbus High School have tested and used, but they are not the only (and likely not the best) methods for building rockets. Always feel free to try new methods and materials.

The third part, *Mathematical Calculations*, is really a supplement to the first two parts. Earlier chapters will refer to parachute designs and simulator results obtained from the formulas and algortihms in Part III. Although it is not necessary to understand these formulas to use the data, they provide the information needed to develop computer models and simulations.

Part I

Rocket Theory

Chapter 1

Ten Common Myths

Myths about rocket design are everywhere. This chapter should help to clear up 10 of the most common misconceptions about the design of water rockets.

Myth #10 – If it looks good, it will fly.
Few students understand the physics principles which determine a rocket's flight. Understanding these principles—forces (thrust, gravity, etc...), drag, and stability—are critical to building a successful rocket. Often, the "this looks about right" method does not work, because large, supersonic rockets are designed differently, because of their high speeds and computer guidance systems. An introduction to rocket design begins in chapter 3.

Myth #9 – Using a heavy nosecone is the most reliable way to deploy a parachute.
There are many better ways to deploy a parachute using an "active" system—one involving spring-loading or rubber bands. Using an airspeed-sensitive flap, these can be set to deploy at apogee, utilizing the maximum height of the rocket, and approaching an 80–95% reliability rate (depending on how well the system is constructed and tested). See chapter 10 for more on active deployment systems.

Myth #8 – Duct tape is the best material for attaching rocket parts, because it is strong.
Duct tape is stronger than necessary for most rocket parts. It adds unnecessary weight to the rocket, which greatly decreases the rocket's performance. (A typical piece of duct tape weighs 3 to 10 grams, decreasing a rocket's time aloft by 1 to 3 seconds for *every piece* of tape used. See chapter 3 for more on the effect of excess weight on rockets.) Packaging tape or mailing tape is a much lighter alternative, and offers sufficient strength.

Myth #7 – All materials on water-powered rocket must be waterproof.
Waterproof materials are not necessary on any part of the rocket, even fins. It is more important to use light materials, instead of waterproof materials. A *stable* rocket will always fly vertically, so that the water inside will be propelled away from the rocket. (Learn how to make a rocket stable in chapter 5.) Of course, use a funnel, and be careful when filling, especially if you use balsa or cardboard on your rocket.

Myth #6 – If the rocket holds together on the ground, it will be strong enough during flight.
A typical rocket experiences 30 to 40 G's of acceleration during launch. This means that during a fraction of a second of the flight, pieces of the rocket has the effective weight of 30 to 40 times their normal weight. For example, a 30 gram parachute will weigh as if it were 900 to 1200 grams! If the platform that supports the parachute is not strong enough to support this much weight, it will likely break during launch. See chapters 13 and 14 to learn more about calculating a rocket's acceleration using computer simulations.

Myth #5 – The amount of water in a rocket has little effect, as long as it is around 50%.
This is false for two reasons:

1. The amount of water has a *great* effect on the rocket's height. In bottle rockets, water is thrust, but it also adds

excess weight. You must reach a compromise between thrust and weight to find the optimum water level.

2. 50% is too much water for a typical rocket. The optimum water level varies for each rocket, depending on weight and drag, but it is typically between 40% and 45% of the bottle's actual volume. (To learn how to calculate the optimum water level using a simulator, see chapters 13 and 14.)

Myth #4 – Adding fins, no matter what type or where they are placed, will improve a rocket's height.
Height is a result of many factors—most importantly, stability. Fins will improve stability *only* under two conditions:

1. The fins must be rigid. They must be able to "push" against the wind, even when the rocket is travelling at speeds over 80 MPH.

2. The fins must be located *behind* the center of gravity of the rocket. Otherwise, they will have the opposite effect, making the rocket *less* stable and *decreasing* the height.

See chapter 5 to learn how to determine the effictiveness of fins.

Myth #3 – Aluminum duct tape is good for attaching fins.
Aluminum duct tape does not work for attaching fins. See myth #4 above—fins must be rigid. If they can be bent back and forth, they are not doing much good. For other parts, aluminum tape is usually a waste of weight. Aluminum tape should only be used *sparingly*, and only on *moveable* parts.

Myth #2 – Bigger parachutes are better.
Yes, bigger parachutes result in a longer time aloft, but bigger parachutes cause extra problems: they are less reliable, they deploy slower, and they are more likely to fly into trees. A large parachute is not necessary for a flight in excess of one minute—a

medium-sided parachute works fine (80 to 120 cm in diameter), and it is much more reliable. Weight is more important factor—you will have much more success if you use a light rocket with a medium-sized parachute.

Myth #1 – Adding weight to the rocket's nosecone will increase the rocket's time aloft.
Adding weight to a rocket's nosecone improves stability, which may improve the rocket's height. But this weight is only beneficial during the first four seconds of the launch. After apogee, as the parachute opens and the rocket descends, the extra weight causes the rocket to fall faster, decreasing the time aloft. There is a way to have the same increase in height, without adding weight: properly placed fins. See chapter 5 to learn more.

Chapter 2

Five Critical Factors

A good rocket design can be summarized in five words: reliability, rigidness, precision, weight, and drag. There is no perfect rocket, but the following five critical factors will ensure that your design is as successful as possible. The factors are listed in their order of importance. For example, do not add weight (#4) to a rocket to decrease drag (#5), and do not select a material that is weighs less (#4), unless it is strong (#2).

2.1 Reliability

Especially in the Science Olympiad competition, where rockets are scored based on time aloft, reliability is critical. To consistently score well, you must have a rocket which reaches its maximum height, and has a parachute that reliabily deploys. Remember, a rocket that consistently gets 20 seconds aloft will on average, score higher than a rocket which reaches one minute, but only works 20% of the time.

Simple designs are not necessarily the most reliable. A semi-complex design, such as an airspeed-deployment system, tends to be significantly more reliable than a rocket which relies on gravity, but *only if it is thoroughly tested.* Testing is the key to reliability. A reliable rocket is the result of thorough testing,

both on the ground, before it is actually launched, and in the air, through numerous launches.

2.2 Rigidness

Rigidness is the most commonly overlooked factor of rocket design, but it is one of the most critical. The simulators described in later chapters will take the shape of the rocket and fins into consideration. If the rocket or any part of the fins is able to flex, there is no way to accurately calculate how it will perform in the air.

Obviously the rocket cannot be perfectly rigid, since we are building it out of light materials such as plastic and balsa wood, but you should always make a reasonable attempt at rigidness. A good test of rigidness is simply by handling your rocket. You should be able to pick up your rocket by *any* part (fins and nosecone included), handle it, shake it around, etc... and *nothing* on the rocket should ever move. If it bends when you handle it, it will definately bend under the 80 MPH of wind from the launch.

2.3 Precision

When working on a such a small scale like water rockets, precision is essential. On deployment systems like the airspeed-flap, one millimeter of adjustment can make the difference between a rocket that is 90% reliable and one that is only 10% or 20%. Precision is also needed for the simulators—one centimeter will make the difference between a stable and an unstable rocket.

Like rigidness, we must be realistic when measuring precision, due to the materials we have to work with. If you take your time when constructing pieces, and do it carefully with a sharp knife, no part of the final rocket should vary by more than 2 or 3 millimeters from your plans.

2.4 Weight

Weight is a misunderstood factor of rocket design. When used in reasonable amounts (80 to 200 grams), rocket weight only has a small effect on the rocket's maximum height. Stability is far more important.

Although the weight of a rocket does not significantly affect its height, it has a great affect on its time aloft. As the parachute on a rocket inflates, the rocket quickly slows down, until it reaches its terminal velocity (which usually takes about 2 to 3 seconds). Once the rocket has slowed to its terminal velocity, it continues to fall at this contant speed until it hits the ground. This is where weight comes in—terminal velocity depends on weight and parachute area-the more the rocket weighs, the greater its terminal velocity, and the faster it will fall. As a general rule of thumb, if you reduce the weight of your rocket by 3 grams, you will increase its time aloft by 1 second.

2.5 Drag

Drag is the factor which primarily determines a rocket's height. It is important to design a rocket with low drag to reach its maximum height, because the higher a rocket is when the parachute deploys, the longer it will stay aloft. Drag, however, is not as important of a factor as weight—drag only affects the first four seconds of the launch (from liftoff to apogee). Weight affects the rocket for the rest of the flight, from apogee, until it touches the ground.

Chapter 3

Forces

So what makes a rocket fly? Of course, it is the pressurized air inside the rocket that propels it upwards, but why does adding water increase the height of the rocket? And how does the size of the nozzle affect the rocket? To answer these questions, we must look at the forces which affect the rocket during its flight.

This chapter provides a brief overview of the forces involved with water rockets. In this chapter, we will only look at the forces, not the actual formulas for calculating them. To learn how to actually calculate these forces, see chapter 13, *Simulators*.

3.1 Liftoff

When the rocket is sitting on the launch pad, the nozzle of the rocket typically fits over some type of rubber or metal stopper, called a "launch rod." For the first few tenths of a second, all of the rocket's propulsive forces are generated by the pressurized air pushing against the launch rod. This pushes the rocket upwards, until the rocket lifts off the launch pad. We call this the "launch rod reaction force."

While the launch rod reaction force may seem insignificant (it only occurs for a fraction of a second), it becomes extremely important when working with a simulator. As a simulator will

show you, the rocket typically reaches a speed of over 10 MPH before it ever leaves the launch pad.

The next force to consider is gravity—the force which pulls the rocket towards the ground. If the launch rod reaction force is not greater than the force of gravity, the rocket will not lift off the ground.

The force of gravity is proportional to the rocket's total mass. At this point, the force of gravity is constant, since the mass is not changing, but in the next stage, this force will be constantly decreasing as water is expelled through the nozzle.

There is one last force to consider—drag. As the speed of the rocket increases, there is a friction with the air, creating a force in the opposite direction of the rocket's movement.

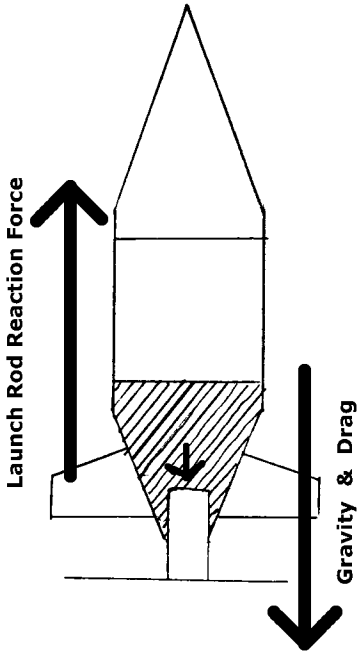


Figure 3.1: Forces at Liftoff

3.2 Launch

Our rocket has cleared the launch pad. We no longer have a launch rod reaction force, but our propulsion now comes from the water inside the bottle. The pressurized air pushes against the surface of the water, causing the water to be expelled through the nozzle of the bottle. This creates a propulsive force, pushing the rocket upward.

Newton's third law of motion states: "For every action there is an equal, but opposite, reaction." In this case, our action is the expulsion of the water out of the nozzle, and our reaction is the propulsive force on the rocket generated by our action.

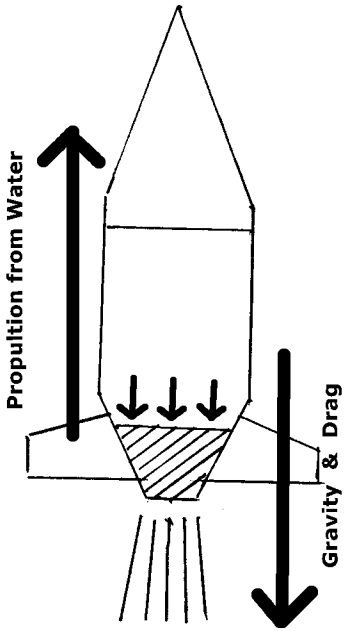


Figure 3.2: Forces during Launch

3.3 Air Pulse

After all of the water has been propelled out of the rocket, the "air pulse" occurs. The air pulse is caused by the remaining air pressure in the bottle leaving through the nozzle, much like the water did earlier. This force is not nearly as great as the one generated by the water, but it is important to consider it.

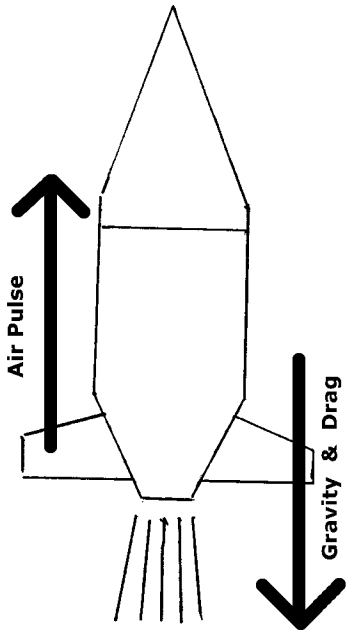


Figure 3.3: Forces during Air Pulse

3.4 Glide

From this point on, our rocket no longer has any propulsive forces. Since it already has so much speed built up, it continues travelling upward, until the forces of drag and gravity finally bring the rocket to a stop. The point at which the rocket's velocity is zero is called "apogee."

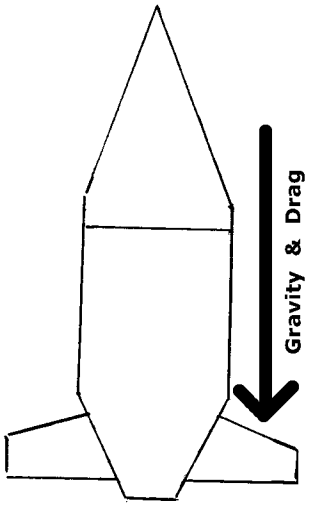


Figure 3.4: Forces during Glide

3.5 Descent

After apogee, the rocket begins to descend. The force of gravity is the same, but one important change has occurred—drag is now an upward force, since drag is always in the opposite direction of the path of the rocket. In addition, we must now consider the drag created by not only the rocket, but also the parachute. From this point on, drag is the force that prevents the rocket from gaining too much speed as it descends. Otherwise, the force of gravity would pull the rocket to the ground in a matter of seconds.

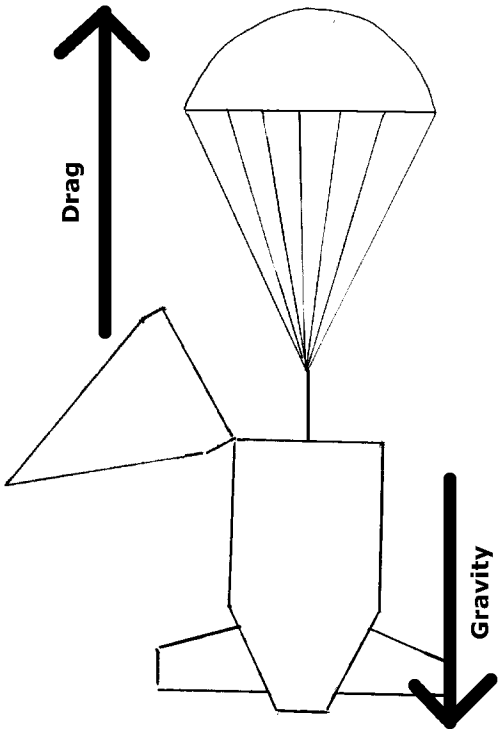


Figure 3.5: Forces during Descent

Chapter 4

Stability

Stability is the single most important factor in rocket design, and it is also the most commonly overlooked. A stable rocket not only goes much higher than one that is only moderately stable, but it also has a much smoother flight, reducing the chance of parachute failures.

One common way to improve the stability is to add weight to the rocket, which does improve the stability (you will understand why later), but a much better way to improve stability is by adding fins. This is not a simple task though. Before adding fins, it is important to understand the factors which contribute to the efficiency of the fins. A rocket with large fins is not necessarily more stable than one with small fins—it depends on the shape and position of the fins, and the shape and weight of the rocket itself. Understanding rocket stability will allow you to make a stable rocket while using the smallest fins, and adding the least amount of excess weight and drag to the rocket.

4.1 What is Stability?

Stability does not necessarily mean to fly in a straight line, or to fly vertically—it is the tendency of a rocket to rotate towards the relative wind. The relative wind is the wind "felt" on the

front of the rocket as it is moving. For example, if the rocket was moving at 50 MPH on a windless day, it would "feel" 50 MPH of wind on the front of the rocket, meaning there is a relative wind of 50 MPH. The relative wind is relative to the movement of the rocket. The relative wind is always in the opposite direction of the rocket.

4.2 Swing Test

One method of determining rocket stability is the swing test. The swing test is done on a ready-to-fly rocket by attaching a string to it on the point where it balances and then swinging it in a large circle (about 10 feet). If the rocket points in the direction that it is swinging, the rocket is probably stable.

The swing test has two major downfalls. First, it can only be done on a ready-to-fly rocket. The only way to test different fin configurations is to actually build the fins and attach them to the rocket. This is not only time-consuming, but can also get expensive—balsa wood is not cheap. The second downfall of the swing test is that it is not an accurate simulation of a rocket's flight. A rocket never actually experiences circular motion as it does in the swing test. Sometimes, a rocket can fail the swing test, but actually be stable when it is launched.

4.3 Center of Gravity and Center of Pressure

Before we look at more advanced methods of calculating stability, we must understand two points and how they contribute to rocket stability: the center of gravity (CG) and the center of pressure (CP).

The center of gravity is the center of the mass of a ready-to-fly rocket. It is the point where the rocket balances, and the point at which it rotates during flight. The center of gravity can either be measured by experimentation (finding the balancing point of the

rocket using string or your finger), or by using force-balancing equations (see any introductory physics textbook).

Just as the center of gravity is the point where the gravitational forces of the rocket balance, there is also a point at which the aerodynamic forces (such as wind resistance) balance. This point is called the center of pressure.

The center of pressure is not nearly as easy to calculate as the center of gravity. Without sophisticated equipment, there is no way to experimentally determine the center of pressure, but there are two mathematical methods to accurately estimate the point: the cross-section method and the Barrowman equations, which will be explained in the next section. The benefit of mathematically calculating the center of pressure, and using force-balancing equations to find the center of gravity, is that we can predict how a rocket will fly from the plans for it, without actually building the rocket. If we find out that the rocket is not stable, we can make changes to the plans before we start building the rocket.

In a stable rocket, the center of pressure must be located aft of the center of gravity. This is because the aerodynamic forces centered at the center of pressure are in the direction of the relative wind (the opposite direction of the rocket). If the rocket is moving up, the aerodynamic forces are pushing down on it.

Now, let's look at how these forces work in flight. The rocket starts off pointing into the relative wind, but eventually, some unpredictable force (uneven drag on the rocket, a small gust of wind, etc.) will cause the rocket to stray from its course. If the center of pressure is located aft of the center of gravity, the aerodynamic forces will work to pull the bottom of the rocket back in line with the relative wind, pointing the rocket back in the direction of the relative wind. This makes a stable rocket. If the center of pressure were foreward of the center of gravity, the opposite would happen. The aerodynamic forces would pull the nose in the opposite direction that it should move, causing the rocket to spin out of control—an unstable rocket.

A rocket is not necessarily stable or unstable. There are many

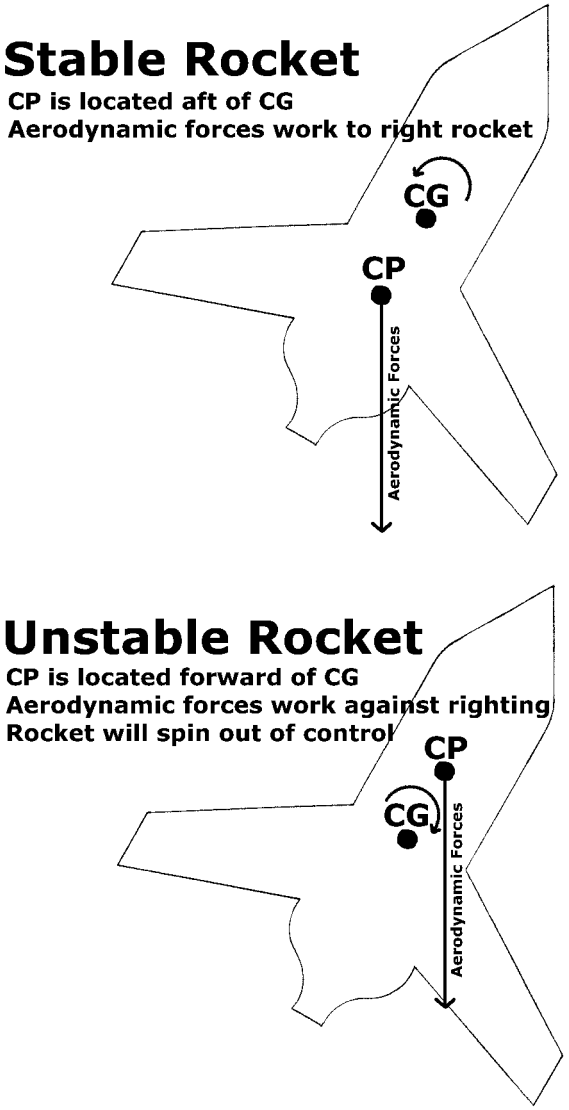


Figure 4.1: The position of the CP in relation to the CG determines stability

different "degrees" of stability—one rocket can be more stable than another. Rocket stability is compared using body calibers. One caliber is equal to the maximum diameter of the rocket (the actual round body, not including fins and other protrustions). The distance between the CP and the CG is referred to as the static stability margin[1]. Thus, if the static stability margin is equal to the diameter of the rocket, the rocket has one caliber of stability.

In general, one caliber of stability or greater means the rocket is stable. A negative stability indicates that the rocket is unstable—it will likely spin out of control, and only get about 30 feet of altitude.

There is one other factor to consider—a rocket that is "too stable." Yes, this is possible. Normal stabilities range from one to three calibers, but too much higher can result in a rocket that is too stable. This can happen when there is a crosswind at the launch site. This crosswind becomes a component in the relative wind, and will cause the rocket to point into the wind, launching off to the side instead of perfectly vertical. The higher the stability of the rocket, the more likely it is to follow the crosswind.

4.4 Cross-Section Method

The simplest method of determining the center of pressure is the cross-section method. If you take a cross-section through the center of your rocket, from the tip of the nosecone, straight down through the nozzle, the center of the surface area of this cross-section will be the center of pressure. You can either find this mathematically, by breaking it up into rectangles, triangles, and other geometric shapes, or you can actually trace your cross-section on a piece of cardboard or other firm material, and find the balancing point of the cardboard. The point where the card-

[1] A positive static stability margin indicates that the CP is aft of the CG; a negative means that the CP is forward of the CG

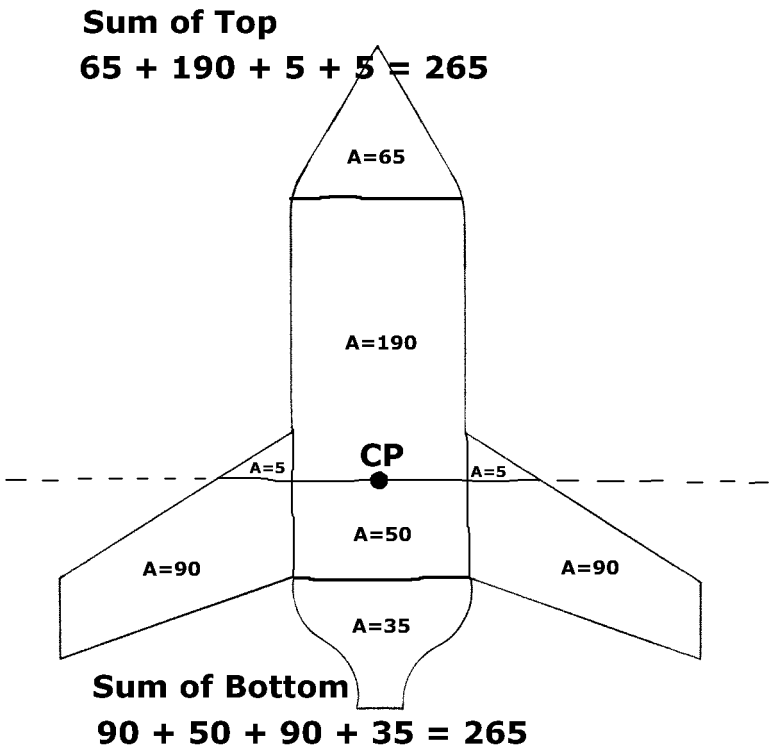


Figure 4.2: The Cross-Section Method finds the center of the surface area of a cross-section of a rocket

board balances (the *center of gravity* of the cardboard) is also the center of its surface area.

There are two main downfalls to this method. First, finding the center of the surface area can be time-consuming. It takes only a few minutes to make the calculations, but it often takes five or ten modifications to a rocket's design before you get the stability just right. A few minutes can quickly turn into a few hours when repeating the calculations over and over again. Second, this method has no way to calculate the effect of different numbers of fins on a rocket. Using the cross-section method, a

rocket with three fins has the same stability as a rocket with four fins, as long as the fins are the same shape and size. Obviously, the one with four fins is more stable, but remember, the cross-section method is only an approximation.

4.5 Barrowman Equations

The most accurate center of pressure calculations come from what are know as the Barrowman Equations. These are a set of equations, developed by aeronautical engineer James Barrowman, which are used to estimate the center of pressure of subsonic rockets. For bottle rockets, which do not even exceed 100 MPH, these equations are more than accurate enough. The best way to use the Barrowman Equations is using a computer simulator, because it will allow you to try different modifications to your rocket to fine-tune its stability. The Barrowman Equations are used commonly by rocket hobbyists, so there is a lot of information about them available on the Internet.

The best calculator for the Barrowman Equations is the *VCP CP/CG Calculator*, available for download as freeware on the Internet. *VCP* allows you to enter your rocket as a series of body sections of varying diameters and masses, add a nosecone and fins, and determine both the center of gravity and center of pressure with a single program. *VCP*'s coordinate system takes a while to familiarize yourself with, but it is well worth the effort.

4.6 Stability Tips

4.6.1 Bottle Shape Affects Stability

One important factor in designing a stable rocket is considering the stability of the bottles used. Different bottles have different natural stabilities. Bottles with a short center-section and a long neck have a naturally high center of gravity. High, that is, if it is used as a rocket; low if the bottle is sitting on a shelf. Many of the

newer bottles are designed this way, because they are less likely to tip over. When we flip the bottle upside-down, to be used as a rocket, this shape works to our benefit, because the center of gravity is already high in the rocket, resulting in smaller fins and less weight that has to be added to make a stable rocket.

4.6.2 Semi-Stable Rockets

One theory in rocket design is to design a rocket that is stable when the nosecone is attached and the parachutes are packed, but with a rocket body that has a negative stability on its own. This can take much fine-tuning in the simulator before it is ever built, but it can be worth the effort when the rocket is actually launched. Semi-stable rockets, such as these, seem to launch normally, like an ordinary stable rocket, but if the parachutes fail during the decent, these rockets decend on their side, due to the body's negative stability, which creates enough drag to drastically slow the rocket down. Not only does this result in a longer time aloft (10 to 15 seconds, versus 6 to 8 with a fully stable rocket), but also causes less damage to the rocket during a crash-landing.

There is one problem with this design: some larger parachutes require the rocket to be falling fast before the parachute will deploy. The parachute may not open until the rocket loses most of its height, or the parachute may not open at all. Problems such as these can sometimes be fixed by using a drogue chute, which will be discussed later.

Chapter 5

Simulator Data

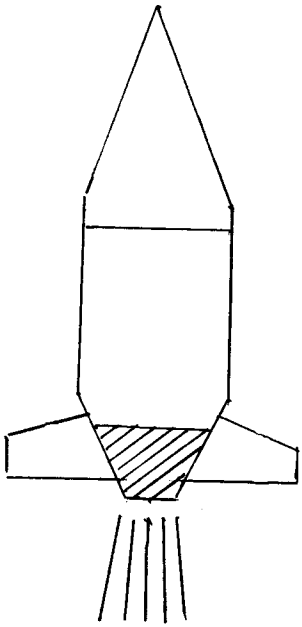
Chapter 13 explains the mathmatics in creating a computer simulator for water rockets. Even without understanding how these simulators work, we can still use the results from a typical simulator to learn how to use this data to build an optimum rocket.

Simulators are great tools for designing water rockets, because they allow you to test numerous factors, such as mass, water level, and parachute size, without the hours of launching required to do traditional experimentation.

There are numerous simulators available on the Internet, which work similar to the methods described in chapter 13. See the *Further Reading* section for more information.

5.1 Typical Launch

We will start by looking at the height, velocity, and acceleration of a typical launch. For this demonstration, we will use a 120 gram, 2 liter rocket with a 1 meter diameter parachute, launched with 40% water at a pressure of 60 PSI. We will also assume that it takes 1 second for the parachute to fully deploy.



5.1.1 Height

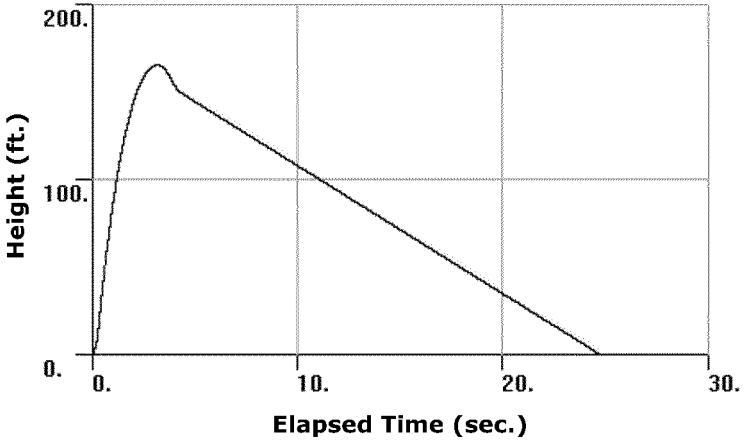


Figure 5.1: Height of the rocket during a typical launch

The height graph provides some interesting data. First and foremost, you should notice that this rocket will stay aloft for 25 seconds (assuming the parachute deploys properly and there is no wind). Next, notice the peak on the left side of the graph—here, the rocket reaches apogee about 3 seconds into the flight, at a height of 170 feet. Afterwards, the rocket begins to pick up speed as the parachute deploys. The rocket loses 15 to 20 feet of altitude before the parachute fully deploys, and the rocket decends at a constant velocity thereafter.

5.1.2 Velocity

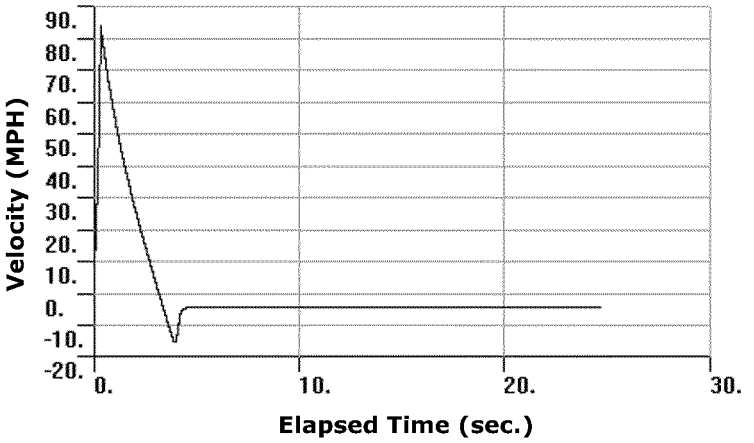


Figure 5.2: Velocity of the rocket during a typical launch

The velocity graph provides two important pieces of data: maximum velocity and descent velocity. For this rocket, the maximum velocity is 84 MPH. This velocity occurs not at apogee, but a few tenths of a second into the flight. Apogee occurs when the velocity is 0 MPH. Once the parachute opens, the rocket slows to its decent velocity, in this case, about -4 MPH. This decent velocity is one of the most critical factors in designing a winning rocket—the slower the rocket falls, the longer it is going to stay aloft.

5.1.3 Acceleration

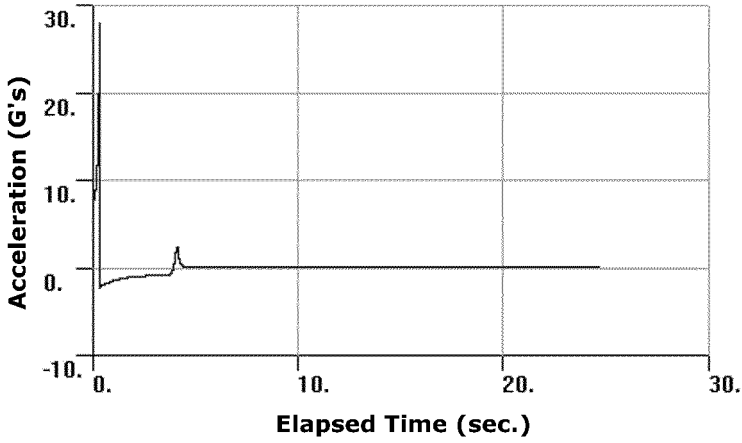


Figure 5.3: Acceleration of the rocket during a typical launch

Notice that the acceleration graph has two spikes in it—a large one a few tenths of a second after launch, and a second, smaller one about 4 seconds into the flight.

The first spike is the important one—it indicates the maximum acceleration of the rocket due to the propulsion of the pressurized air and water. During this launch, the rocket will experience 28 G's, or 28 times the force of gravity, as it ascends. This value is important to consider when building rockets—a small, 30 gram parachute, will have the effective weight of $30 \times 28 = 840$ grams during launch! If the parachute hold is not strong enough to support the weight of 840 grams, it will likely break.

The second spike is caused by the rocket slowing down as the parachute inflates. The value of this spike is typically not important, because it is small compared to the acceleration due to the pressurized air and water.

5.2 Water Volume

Simulators are great for finding the optimum water level for a rocket. Sure, you could test your rocket with various amounts of water to find the optimum level, but that would be tedius. Plus, accurate testing is often not possible, because wind and other uncontrollable factors get in the way.

Finding the optimum water level is important. Most people typically use around 50%, but you can usually get an extra 10 to 20 feet of height by finding the optimum water level (typically 40% to 45% of the bottle's volume). A few feet may not sound like much, but since a typical rocket with a parachute decends at 2 to 3 feet per second, this extra height results in another 5 to 10 seconds of time aloft.

Comparing the two graphs on the next page illustrates an important point about optimum water levels—it varies depending on the rocket. Heavier rockets, and ones with greater drag, require a greater volume of water to reach their maximum height. For most rockets, the optimum volume will be 40% to 45% of the volume of the bottle.

Once you find the optimum water level for your rocket, it is important to be able to consistently measure that volume of water into your rocket. See Appendix A, *Water Markings*, to see a simple system for measuring the water level inside your pressurized bottle.

5.3 Mass

Just as there is an optimum water volume to get the maximum height, there is an optimum mass to reach the maximum height. This optimum mass varies, depending on the rocket's drag.

The optimum mass for rockets is typically very low. Very rarely will you have to add weight to your rocket to reach the optimum mass. Normally, a stable, aerodynamic rocket with parachute weighs more than the optimum mass, but this value

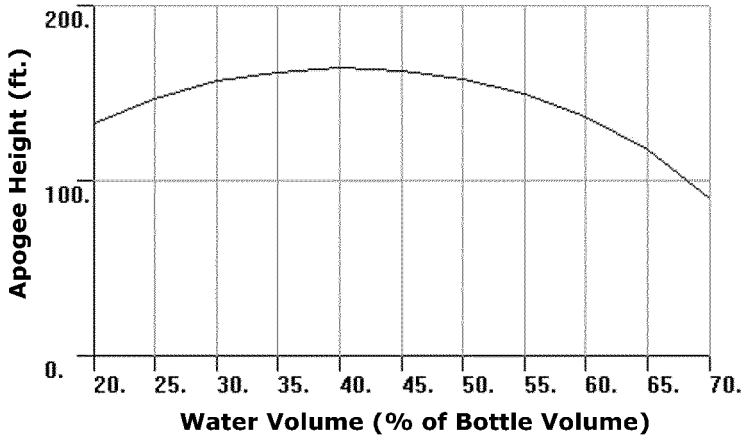


Figure 5.4: Optimizing water volume for a 120 gram, 2 liter rocket

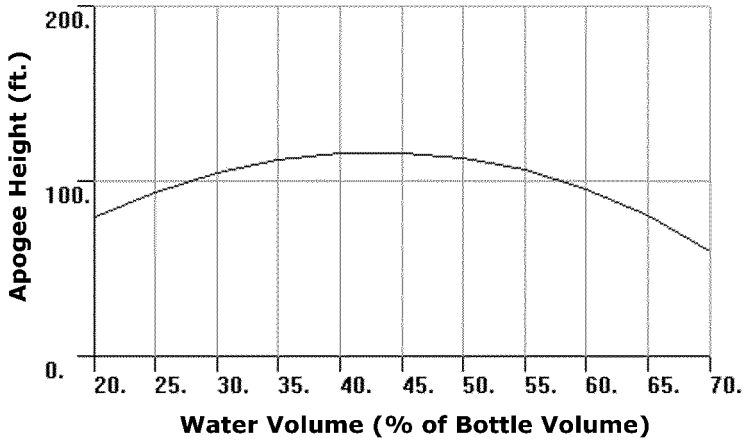


Figure 5.5: Optimizing water volume for a 250 gram, 2 liter rocket

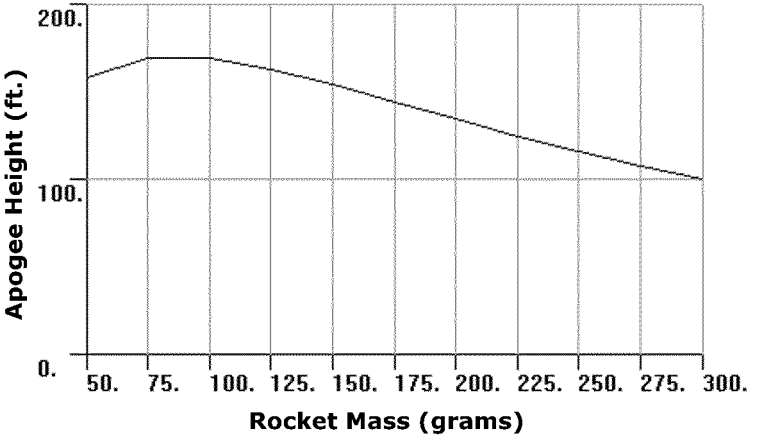


Figure 5.6: Optimizing mass for a 2 liter rocket with 0.2 drag coefficient

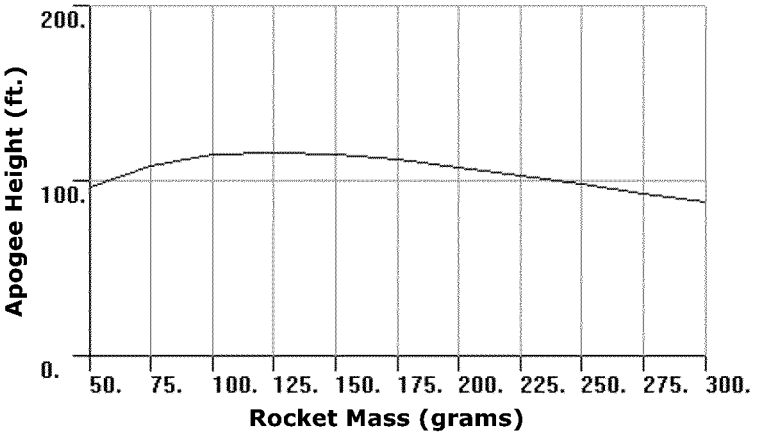


Figure 5.7: Optimizing mass for a 2 liter rocket with 0.5 drag coefficient

will give you a good goal for the weight of your rockets.

As you can see from the graphs on the previous page, the optimum mass for a 2 liter rocket is typically between 75 and 125 grams. These values are deceptive though—these are the optimum masses to get the maximum *height*. The optimum mass to get the maximum *time aloft* is typically much lighter, because weight causes the rocket to fall faster, especially when it is decending with a lot of drag (when the parachute opens). It is better to have a light rocket decend from an altitude of only 100 feet, as opposed to a heavy rocket decending from 120 feet.

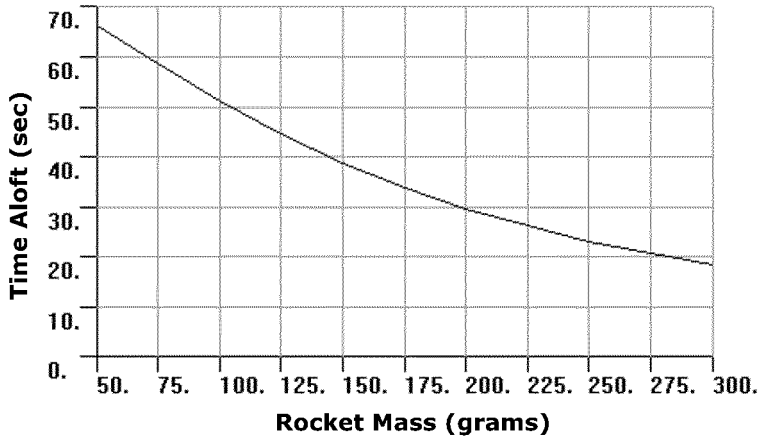


Figure 5.8: Optimum mass can be deceptive—under certain conditions, additional weight will increase height, but it will actually cause the rocket to fall faster.

If your rocket weighs less than the optimum mass, there is a simple solution: bring your rocket up to weight by adding additional parachute. This will not only increase the height of your rocket, but it will also result in a slower decent and longer time aloft.

Part II

Rocket Construction

Chapter 6

Fins

In Chapter 4, we learned to calculate the shape and size of fins for a rocket, but building them can be another challenge.

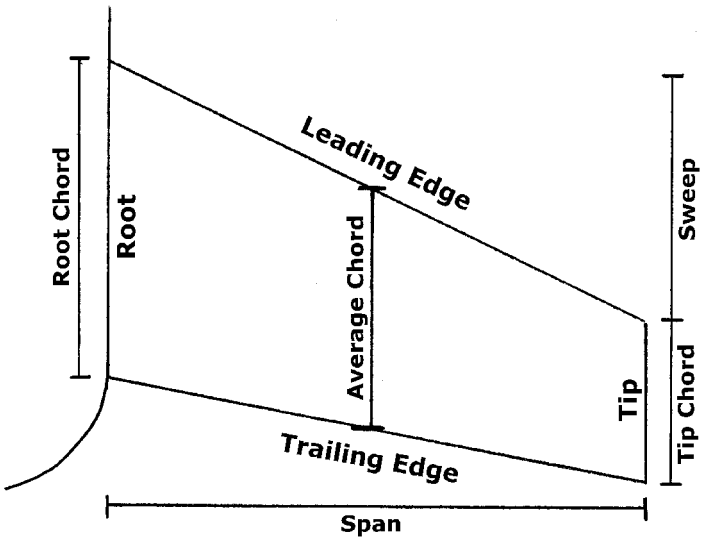


Figure 6.1: Fin Dimensions and Terminology

We will start by looking at the simplest fins, single-ply fins. These work well for rockets which need only small fins to make them stable, but as rockets are built larger and lighter, they require larger fins that must be reinforced. We will look at these "3–dimensional" fins too.

6.1 Single-Ply Fins

A single sheet of light plastic or wood is adequate for most basic fin designs. ($1/16^{\text{th}}$ inch balsa wood works best) They are the simplest and easiest to fins to make, but they have a weakness: plastic will bend and balsa will break.

6.1.1 Fin Patterns

One useful tip before constructing a set of fins is to make a pattern on a sheet of paper. Be sure to keep it in a folder or other safe place, because you will need it to build replacement fins. Single-ply fins usually last only a few launches, so it is best to plan ahead and build extras.

Also, a fin pattern can be useful for building fins with various angles. Simply make a copy of the fin pattern, cut it out, and trace it on to the material.

6.1.2 Constructing

Building fins is simply a matter of taking your time and carefully cutting the balsa with a sharp knife, but there is one important tip when constructing fins: **When using wood, always cut fins with the grain of the wood parallel to the leading edge!** This makes fins much stronger and less likely to break during flight.

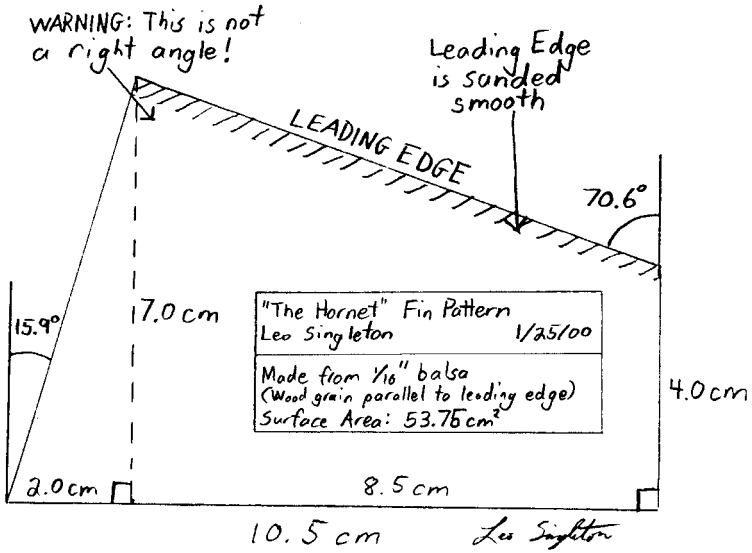


Figure 6.2: A sample, single-ply fin pattern from *The Hornet*

6.1.3 Breaking Point

As we said before, the downside of single-ply fins is their low breaking point. As a general rule, on a normal rocket, launched at 60 PSI, the maximum span of a single-ply balsa fin is between 10 and 15 cm. Remember, this rule applies when the grain is cut parallel to the leading edge. Fins with grains cut in other directions sometimes fail with a span only 5 to 10 cm.

Since the 10 to 15 cm rule applies to $1/16^{\text{th}}$ inch balsa wood, you can sometimes get away with a few extra centimeters of span by using $3/32^{\text{nds}}$. This is usually not a good idea, because it adds extra drag and weight. 3-dimensional fins are usually a better solution.

An important sign of fins that are approaching their breaking point is "fluttering." Fluttering occurs when the air traveling over the fins causes intense vibrations and will lead to structural failure. Sometimes fluttering is minimal, and only causes a hum-

ming noise as the rocket lifts off, but take this as a warning—when fluttering gets too bad, the fins will rip apart.

6.2 Reinforced Balsa Fins

Reinforced fins, or "3-dimensional fins," are made of three separate layers of balsa wood glued together to form a strong, but light fin. Reinforced fins have much more strength than single-ply fins, and can be used when extra stability is needed.

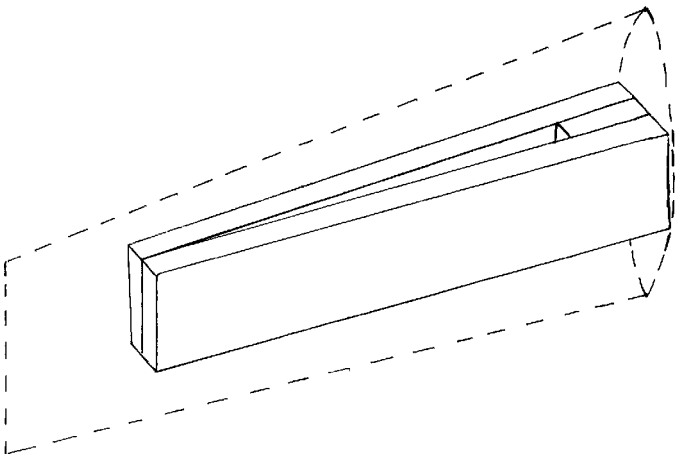


Figure 6.3: Internal balsa structure of a reinforced fin

Reinforced fins are constructed using two strips of $1/16^{\text{th}}$ inch balsa wood, approximately 1/2 to 3/4 of an inch in width and have a length of about $2/3^{\text{rds}}$ of the span of the fin. A third, smaller piece of $1/16^{\text{th}}$ inch balsa is placed in between the other two strips, to increase the thickness of the fin at the root. As usual, make sure the grain of the wood is parallel to the leading edge.

The internal structure is then covered with $1/32^{\text{nd}}$ inch balsa wood, which makes up the actual surface of the fin. The two pieces are first glued to the internal structure, then their edges

are glued together. ($1/32^{\text{nd}}$ balsa is very flexible) For decreased drag, the edges of the fin can later be sanded down to a smooth edge.

6.3 Other Materials

Fins do not necessarily have to be made from balsa wood. Balsa is simply a light material that is relatively easy to work with. Any type of plastic, cardboard, or other material can be used for fins, as long as it is rigid. Remember, the stability simulations in the previous chapter *assume* that the fins on the rocket are rigid. Fins that are not rigid will have no effect on a rocket's stability.

6.4 Attaching Fins to Rockets

A good fin is useless unless it is attached to the rocket well. Like a fin, the joint should be rigid, and prevent the fin from moving around. Materials such as duct tape (even aluminum tape) do not work well, because they allow the fin to move back and forth during flight, making the fin useless.

The best way to attach fins to a rocket is by using a strong glue, such as a super glue or hot glue. Medium-set Jet glue works best.

Unfortunately, Science Olympiad rules prohibit using super glues or hot glues directly on the pressurized bottle. We can work around this by cutting strips of plastic from another bottle. The strips should be the length of the fin, and about one inch wide. **Before using super glue on the plastic, be sure to thoroughly sand it with a light sandpaper (500 grit or lighter), until the plastic becomes translucent.** Otherwise, the glue will not stick to the plastic! Apply a few drops of glue to the plastic and set the fin in place. Once the glue hardens, apply a full bead of glue to each side of the fin for extra strength.

Now you can attach the strips of plastic to the rocket using mailing or packaging tape. (Scotch extra-strength mailing tape

works well.) **When taping fins to the rocket, be sure to completely cover the top of the plastic strip with tape!** If the top of the strip is not taped, air can get underneath during launch, and the fin will rip off.

6.5 Extra Reinforcement

Although super glue works well for attaching fins to rockets, this joint can never be too strong. Remember, by Science Olympiad rules, if the fin breaks off during launch, the rocket is automatically disqualified.

For extra reinforcement, a flexible, caulk-like glue works well. After the super glue has dried, run a small bead along each edge of the joint, and let it dry for at least 24 hours.

Chapter 7

Parachutes

Once we have covered the basics, and can build a rocket that is stable, it is time to start working on the next aspect: parachutes. A simple plastic bag will work if you're only looking for a few seconds aloft, but a competitive rocket requires a much better parachute. As you will see, building a good parachute can be as complicated as building the rocket itself.

7.1 Dome Parachutes

First, we will look at dome parachutes. These parachutes are made from multiple panels of fabric, sewn together to form a dome shape—far more efficient than the typical flat parachutes used in model rocket kits.

Parachutes work by trapping air to create drag. For a flat parachute to work, it must first inflate, by forming a domed shape to catch the air. When this happens, only half of the parachute is used to trap air, while the other half flaps around uselessly. A dome-shaped parachute solves this by "fitting" the shape of the air, so all of the parachute's surface area is used.

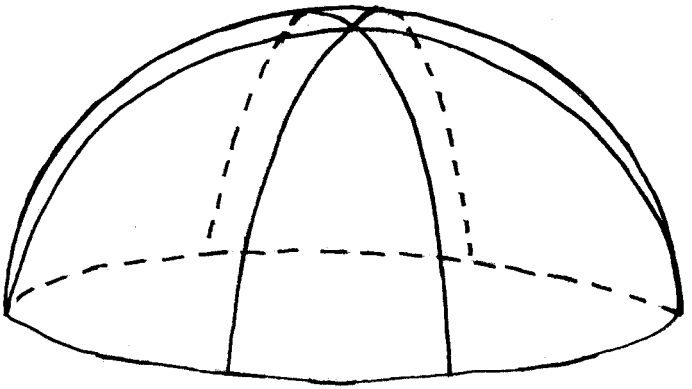


Figure 7.1: A 6-panel dome-shaped parachute

Dome-shaped parachutes are constructed out of three or more pieces of material (usually plastic). These panels are attached together like a beach ball, with panels attached side to side, with every panel meeting at a single point at the top. There is no exact formula for determining the number of panels needed for a parachute, but here are some typical values:

Parachute Diameter	Parachute Type	Typical Number of Panels
< 40 cm	Small Drogue	4
40 - 60 cm	Large Drogue	6
60 - 100 cm	1-Liter	8
100 - 130 cm	2-Liter	8

A top view of the parachute shows how the panels are connected. The panels of a 6-panel parachute appear to be six triangles, but the panels are not actually triangular. They are flattened out *spherical triangles*—the sides are no longer straight when mapped in two dimensions.

Although dome-shaped parachutes work extremely well, there is still a way to improve them further: elliptical parachutes.

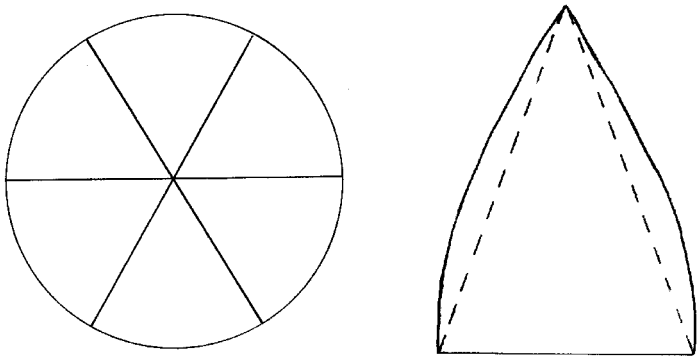


Figure 7.2: Left: A top view of a 6-panel dome-shaped parachute. Right: A single panel of the same parachute. Notice that the panel is no longer triangular-shaped when it is laid flat.

7.2 Elliptical Parachutes

Elliptical parachutes are essentially stretched-out versions of dome parachutes. They allow the parachute builder to make a larger parachute with the same amount of material. Thus, elliptical parachutes are lighter and deploy faster than their equivalent dome-shaped parachute.

In a dome-shaped parachute, the radius equals the height, but in an elliptical parachute, the height is less than the radius (typically 70% of the radius). This ratio has a give–and–take effect. As the height decreases, the parachute requires less material, but loses efficiency. Eventually, if the height is decreased all the way to zero, we are back to a circular parachute.

7.3 Constructing a Panel

The first step in building a parachute (either dome or elliptical) is to build a pattern for one panel of the parachute. For now, we will assume that you already have the coordinates that form the

curve of your panel—in Part III you will learn how to calculate coordinates for parachutes of any shape and size.

Here is the output from a parachute calculator. We will use these values to construct our pattern:

```
Diameter: 100 cm
Height: 50 cm
Bottom Overhang: 10 cm
# of Panels: 8
# of Calculated Points: 10

Panel Coordinates:
(+/- 0.00 cm, 78.54 cm)
(+/- 3.41 cm, 69.81 cm)
(+/- 6.72 cm, 61.09 cm)
(+/- 9.82 cm, 52.36 cm)
(+/- 12.62 cm, 43.63 cm)
(+/- 15.04 cm, 34.91 cm)
(+/- 17.00 cm, 26.18 cm)
(+/- 18.45 cm, 17.45 cm)
(+/- 19.34 cm, 8.73 cm)
(+/- 19.63 cm, 0.00 cm)

Vertex of Overhang Arc: (0 cm, 14.28 cm)
Radius of Arc: 24.28 cm
Angle of Arc: 1.8842 radians
```

To construct our pattern, first, find a large enough piece of posterboard. (You can use heavy paper, but posterboard works best) Also, this posterboard needs to be white, or another light color—you will be making a lot of pencil marks on it before we get to our actual shape.

To determine the size we need, look at our panel coordinates: the x values range from -19.63 to 19.63, thus we need a width of about 40 cm. Our y values range from 0 to 78.54, but notice that we have an overhang of 10 cm, so we actually need a height of about 90 cm.

Once we have our posterboard, we need to draw our x- and y-axis. It is important that these are perpendicular, because we will base all of our other measurements on them. Make sure that they are perpendicular by using the corner of a sheet of paper to mark the right angle. As we stated before, our x-axis needs to range from -19.63 to 19.63 cm, and our y-axis needs to range from -10 to 78.54 cm. You can always make the axes longer than these measurements—those are just how much our pattern will occupy.

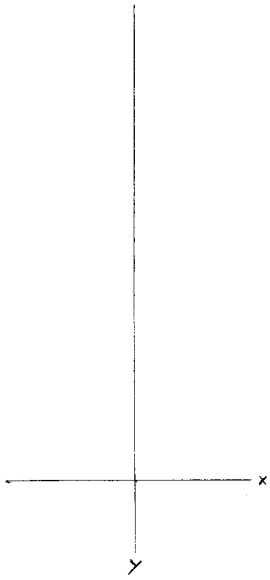


Figure 7.3: Axes for our 100 cm dome parachute

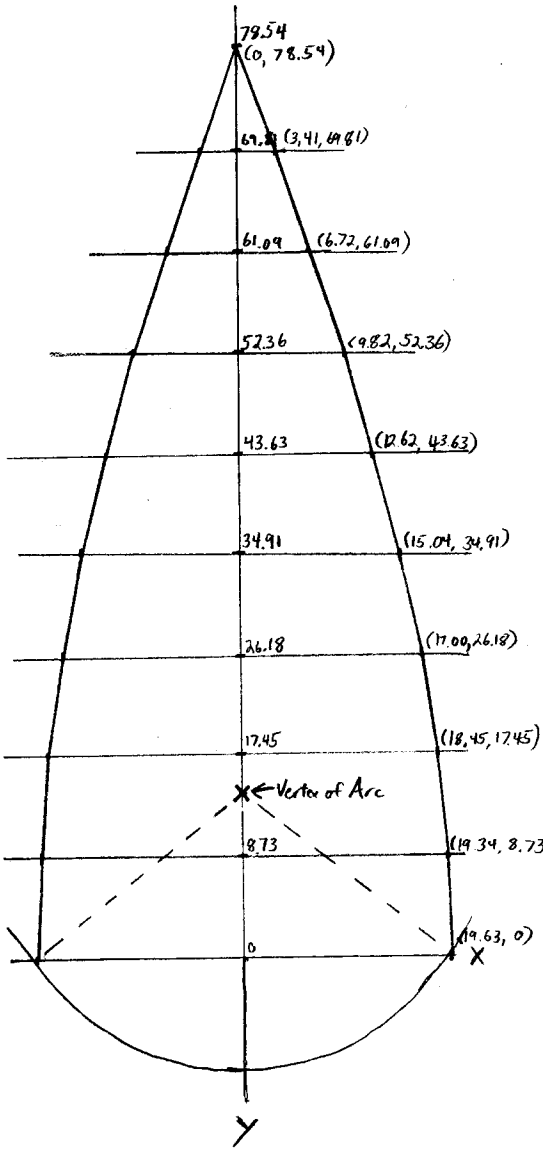


Figure 7.4: Completed pattern for a 100 cm dome parachute

Once we have our axes, we can mark off our y values on our y-axis. These should be equidistant, as we will show in our next chapter.

Once we have our y values marked, the next step is to measure out the corresponding x values and mark our points on the posterboard. Connecting these points should give us the curved sides of our panel.

Finally, we construct our overhang. Overhang is an arc, so we must first find and mark this coordinate, (0, 14.28), on our posterboard. Next, construct the arc using a compass. If it is large parachute, as in this case, a standard compass will not be large enough. You will have to use two pencils and a piece of string. (A piece of posterboard with holes punched in each end also works well.)

Now, we can cut out our pattern and use it to trace onto our panel material. Use a dark marker to trace your pattern onto your material. When cutting, **do not cut directly on the lines**! You must leave room for a seam to attach panels with. The width of this seam depends on the method you will be using to attach panels together. Also, if you will be using a soldering iron or wood burner, you will cut the panels and melt them together at the same time, so do not cut them out yet.

7.4 Methods of Construction

7.4.1 Glue or Tape

Glue or tape can be used to attach panels together, but it does not work well. Tape and glue both add a great deal of weight to the parachute, and make the parachute stiff.

7.4.2 Iron

Panels can be melted together using an iron. Place two panels, one on top of another, on an ironing board, and place your posterboard pattern between the two pieces of plastic. This will

prevent the panels from melting together anywhere except for the seams, which will be hanging over the edge of the pattern. Cover both of these with a cloth or towel, and then iron the seam for 10 to 20 seconds. Allow a few seconds for the plastic to dry, then pull out the towel and the pattern. The plastic panels should be melted along the seam into a single piece of plastic. If not, repeat the same process and try again.

7.4.3 Soldering Iron or Woodburner

The best way to attach panels together is to use a low-power soldering iron or woodburner. This method creates the smallest seam, compared to the other methods, and thus, creates the lightest parachute with the most flexibility.

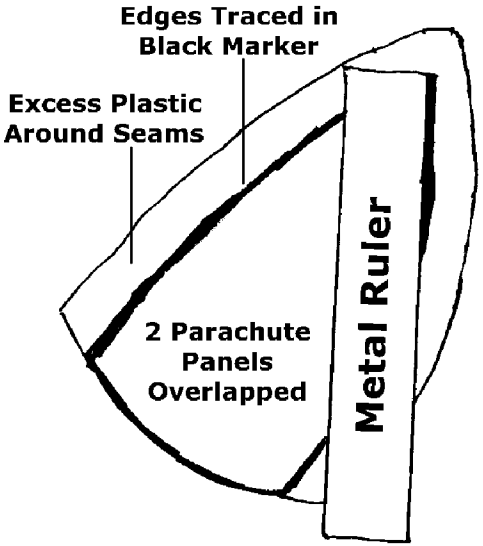


Figure 7.5: Using a metal ruler and soldering iron to attach parachute panels

If your soldering iron or woodburner is too hot, causing the plastic to melt too fast, you can reduce the power by installing a dimmer switch, used for lights, to reduce the power.

Take two panels (do not cut them out), and lay them on top of each other so that the lines you traced from the pattern overlap. Working piece–by–piece along the curve, take a metal ruler and hold it along the line. While pressing down on the metal ruler, run the soldering iron along the ruler's edge. It should make a nice cut, approximately 1 mm in width, and in the process, it will melt the edge of the two pieces of plastic together. If the soldering iron cuts through the plastic without melting the panels together, increase the temperature of the soldering iron.

Repeat this process to attach all of the panels together, making sure that the seams are all on the same side. If the parachute is made carefully enough, the tops of the panels will meet in a single point, and a top panel will not be needed.

7.5 Shroud Lines

Shroud lines are attached to the bottommost point on each panel of the parachute (in the overhang area). The very purpose of the overhang is to attach shroud lines—they help to distribute the force of the shroud lines, and prevent them from pulling the parachute closed.

To attach shroud lines, first place a piece of tape where you want to attach the line. Do this on both sides of the plastic. Then, use a hole punch to cut a hole through both layers of tape and the plastic. **Do not use scissors to cut the hole!** A round hole is less likely to tear when the shrouds are pulled tight.

For an even stronger hole for attaching shrouds, touch the tape with a hot woodburner or soldering iron. This will melt a hole through the parachute and both pieces of tape, but it will also cause some of the plastic to bead up around the edge of the hole. Once cooled, this will form a hard, protective ring and prevent tearing of the parachute.

Many different materials can be used for parachute shroud lines. Most types of string work fine, but of course, the stronger and lighter, the better. Do not use fishing line. Fishing line tends to hold its shape, and not want to flex. It is more likely to get caught or tangled than regular string.

Dacron is one of the best shroud materials available, not only because it is strong and light, but because it does not hold its shape when coiled for a long period of time. Dacron can be found in many stores and hobby shops, often sold as kite string.

Shroud length is also an important consideration. Typically, shrouds should be 2 to $2\frac{1}{2}$ times the diameter of the parachute, but this is often not practical for Science Olympiad rockets, which have a maximum length of 3 meters. Usually, shrouds that are 1 to $1\frac{1}{2}$ times the diameter will suffice, and allow you to put the largest parachute possible within the 3 meter limit.

Chapter 8

Parachute Deployment Systems

The best parachute is dead weight without a good parachute deployment system. This is the most critical part of any rocket, since it determines the difference between a one minute launch and a six second launch.

There are many different methods for deploying a parachute on a bottle rocket, ranging from the simplest gravity system to a complex airspeed flap design. We will look at both of these deployment systems and how they work.

These are not the only two reliable ways to deploy a parachute. Other methods, such as using a balloon or wind-up timer, can be found on the Internet. See the *Further Reading* section for helpful links to get started.

8.1 Gravity Deployment

The theory behind gravity deployment is simple: heavier things fall faster[1]. Therefore, if the rocket body weighs 60 grams, but

[1]The laws of physics may appear to contradict this statement, but only in a vacuum. When forces such as wind resistance are taken into consideration, heavier things fall faster

the nosecone weighs 80 grams, the nosecone will fall faster, separating from the nosecone. Then, if the length of the string attaching the nosecone to the body of the rocket is longer than the total length of the parachute (including shrouds), the parachute will deploy.

This system is the "quick and easy" way to get a parachute deployed on a bottle rocket, but it has three major downfalls: First, this system is not very reliable—even if you have a great difference in the weight of the body and nosecone, there will still be occasional failures for no reason. Second, this system requires a long string for the nosecone, which under the Science Olympiad limit of 3 meters, drastically reduces the parachute size that you can use. Third, rockets that use this system are *heavy*! For a realiable rocket, you will need the weight of the nosecone to the body in at least a 2:1 ratio (e.g. a 200 gram nosecone with a 100 gram body). The very principle that makes this system work is what makes it so unusable—a 300 gram rocket falls fast, even with a parachute[2].

8.2 Airspeed Flap Deployment System

The airspeed flap solves all the problems of gravity deployment—once it is finely tuned, it is extremely reliable, adds no additional length to the rocket, and it adds only a mere 5 to 10 grams to the weight of the rocket.

The airspeed flap was originally designed by Dave Johnson, but there are now many variations of its design. The design presented here is a unique variation developed by Columbus High School. For more information on Dave Johnson's original system, you can find the address of his web site in the *Further Reading* section of the handbook.

[2]Our record for a gravity-deployed rocket is 23 seconds

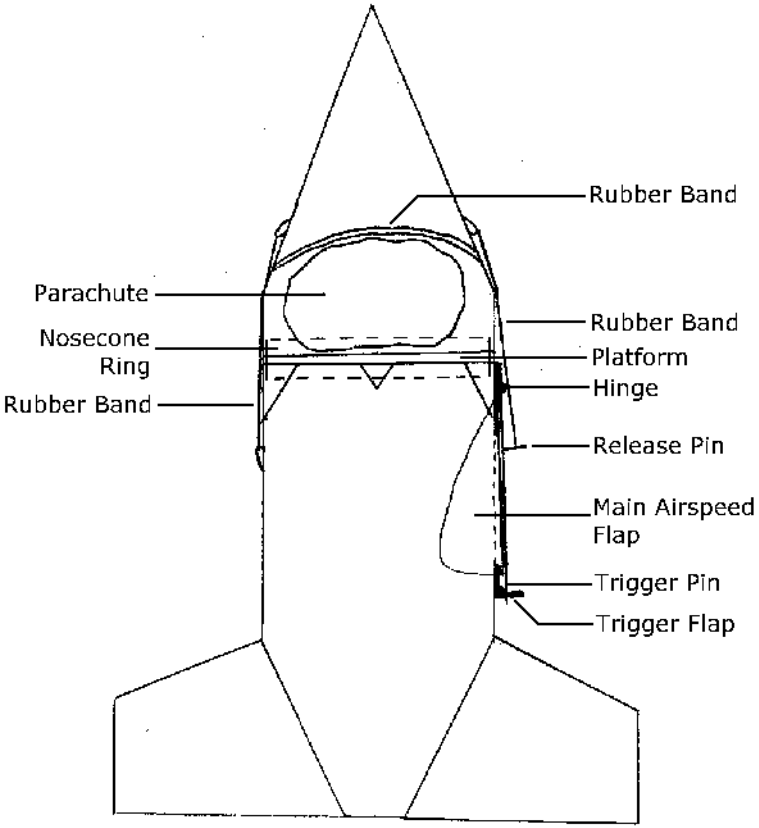


Figure 8.1: A typical Airspeed Flap Deployment System

The main component of this system is the airspeed flap—a small flap of plastic (made from the mid-section of an empty bottle) that is hinged at the top and attached to the side of the rocket body. This airspeed flap will be held against the rocket body by the force of the wind during launch. At apogee, the wind will no longer be strong enough to hold the flap down, so it will open, and release the nosecone.

To prevent the main airspeed flap from deploying while the rocket is on the launch pad, a trigger flap is used. The trigger flap is released by the force of the wind from liftoff.

The nosecone sits on top of the rocket, and is held in place by two rubber bands—one on each side. One rubber band is attached to the rocket body, while the other is hooked on to the main airspeed flap. These rubberbands work as opposing forces—if they are tensioned properly, they will hold the nosecone in place during the launch. Once the main airspeed flap opens, the rubber band attached to it will be released. The nosecone will be pulled off by the rubber band on the other side, releasing the parachute.

8.2.1 Platform

Before constructing an airspeed flap deployment system, you must first flatten out the top of the rocket body using a platform made of light cardboard or plastic. The parachute will sit on top of this platform.

To prevent the nosecone from slipping off of the platform during launch, cut a small ring out of the mid-section of another bottle. Mount the ring around the platform, leaving only $1/8^{\text{th}}$ to $1/4^{\text{th}}$ of an inch protruding above the platform.

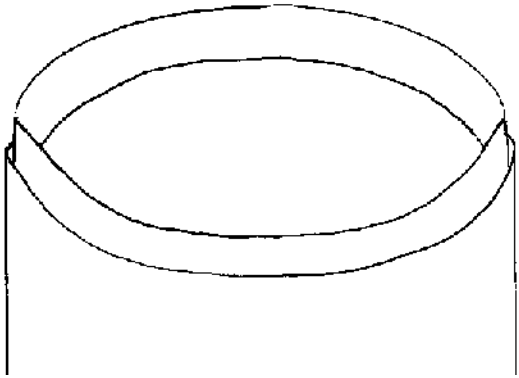


Figure 8.2: A platform with nosecone ring

8.2.2 Nosecone

As stated above, the nosecone should have a rubber band attached to each side of it—one will be attached to the rocket body; the other to the main airspeed flap. Place another rubber band on the inside of the nosecone. Once there is a parachute on the platform, this rubber band will act as a "spring" to push the nosecone off. For even better results, use two rubber bands on the inside, and attached them in a cross.

8.2.3 Main Airspeed Flap

The main airspeed flap is constructed from the mid-section of another bottle and hinged at the top. The main airspeed flap should have two pins attached to it. You make these pins from paperclips or wire, or you can replace the pins with plastic to avoid using metal parts. The first pin is located near the top, and is perpendicular to the surface of the flap. This pin will be used to hook the rubber band going to the nosecone. The second pin is located at the bottom of the flap, pointing down. The purpose of this pin will be explained in the next section on the trigger flap.

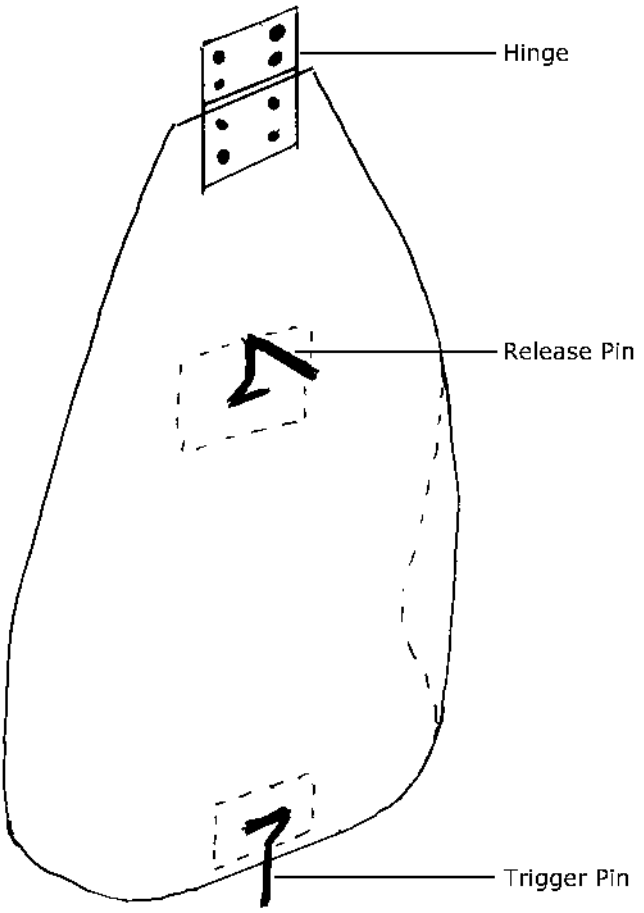


Figure 8.3: Main Airspeed Flap

8.2.4 Trigger Flap

The purpose of the trigger flap is to hold the main airspeed flap down while the rocket is on the launch pad. It can be made of a small hinge, with a hole drilled on one side. The pin from the bottom of the airspeed flap can be placed through this hole to hold the main flap in place. During launch, the trigger flap will be forced down by the wind, releasing the main airspeed flap.

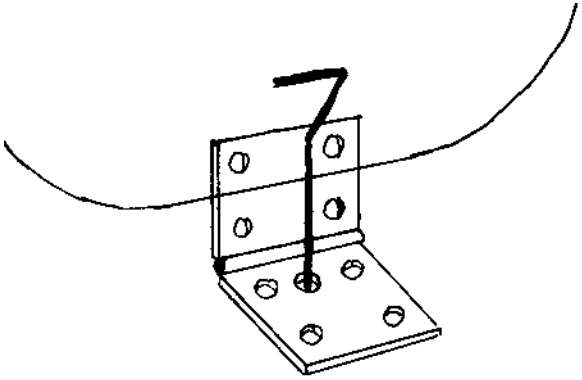


Figure 8.4: Trigger Flap and Trigger Pin

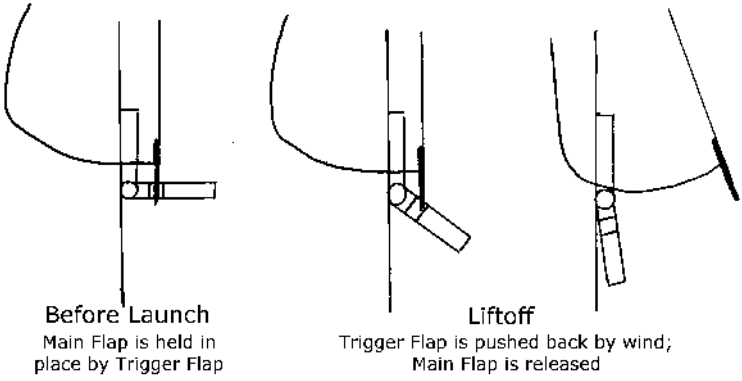


Figure 8.5: The Trigger Flap releases the Main Airspeed Flap

8.2.5 Tensioning the Rubber Bands

The airspeed flap deployment system only works if the rubber bands are tensioned properly. The best way to test it is by setting the main airspeed and trigger flaps, then blowing on the flaps to simulate the wind from the launch. With one large breath, you should be able to release the trigger flap and still hold the main airspeed flap down. If the rubber bands are tensioned right, the nosecone will spring off as soon as you stop blowing on the main airspeed flap. If not, try different combinations of rubber bands to get the right tensions.

8.3 Airspeed Flap With Drogue

To further improve the airspeed flap design, we can add a second parachute compartment and a drogue parachute to the design. A drogue parachute (typically 30 to 50 cm in diameter) is designed to deploy quickly. When it is attached to the top of the main parachute, the drogue will help to inflate the main parachute faster. For consistent, quick deploys of large parachutes, use an airspeed flap to deploy the drogue chute and let the drogue pull the main chute out of its compartment.

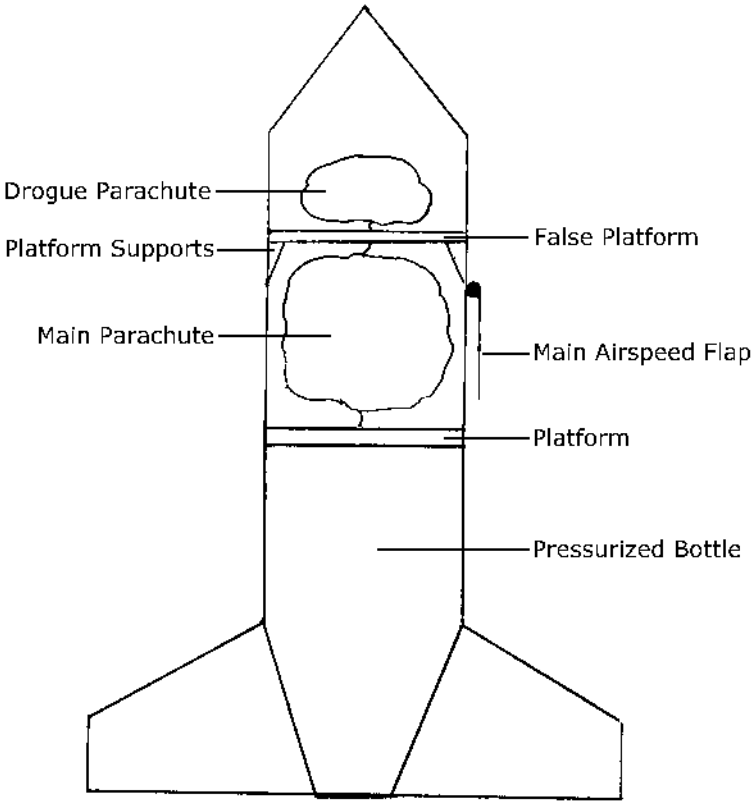


Figure 8.6: Typical Airspeed Flap Deployment System with Drogue Parachute

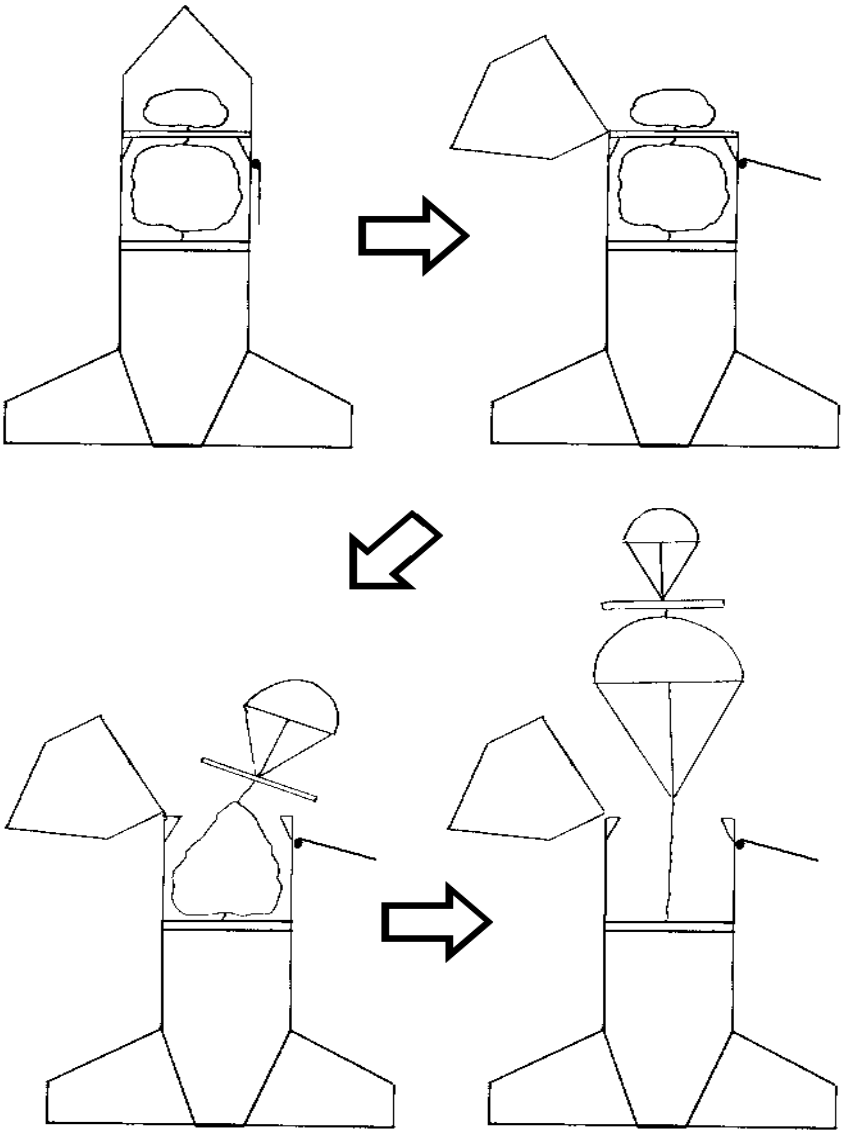


Figure 8.7: Main Airspeed Flap releases nosecone; Drogue Chute pulls out False Platform and inflates Main Parachute

Chapter 9

More Parachute Tips

9.1 Packing Parachutes

The best way to pack a parachute is using the "z-fold." Hold the parachute from the top and stretch it out into a long roll. Then, fold the parachute back and forth every two to three inches, depending on the size of your parachute hold.

At competition, it may be necessary to pack your parachute before competition, hours before it is actually launched. If this is the case, sprinkle baby powder over the entire parachute (inside and outside) before you fold it, and continue to sprinkle baby powder as you fold the parachute. Baby powder will help prevent the plastic from sticking together. It is best to test this a few times before competition, to make sure the parachute does not expand or get stuck in the parachute hold.

9.2 Testing Parachutes

Sometimes, you may have to test your rocket in less–than–ideal conditions. If the wind gets too heavy, and could possibly blow the rocket into nearby trees or obstructions, it is best to test the rocket without using full parachutes. Testing with smaller parachutes is a possibility, but on light rockets, parachutes are

used as ballast, and they are critical to a rocket's stability. It is better to test with full parachutes, while restricting the parachute from fully opening with a twist-tie. To do this, stretch the parachute out, as if you were about to do a z-fold. Take the twist-tie, and tie it around the middle of the parachute. This will restrict the parachute to approximately a third of its normal surface area. If you need to use even less parachute area, move the twist-tie down further.

9.3 Multiple Parachutes

Multiple parachutes are possibly a way to get more parachute surface area, but they create many additional problems, and are probably not worth the effort.

On multiple-parachute rockets, there is a good chance that one or more of the parachutes will get tangled. Extra precautions must be taken when folding parachute shrouds.

Another serious problem is that on a multiple-parachute rockets, the parachutes usually inflate at different times. Often, only one will inflate for the first five to ten seconds of flight, because it reduces the speed of the rocket, which prevents the other parachutes from inflating.

9.4 Parachute Age

It is important to keep track of parachutes ages and the plastic that they are made from. Mixing parachutes of different ages (either as multiple parachutes or a main–drogue combination) can cause problems. As parachutes age, they become stiffer and require a greater velocity to inflate. Often, only the newer parachutes will deploy, causing the older parachutes to become dead weight that only increases the chances of getting the parachutes tangled.

9.5 Shroud Tangling

Shrouds getting tangled can be a problem in rockets. For multiple-parachute rockets, it is best to keep the shrouds in different parachute compartments. For single-parachute rockets, the best solution is to attach a fishing swivel between the shrouds and the rocket body. This will allow the parachute to roll and spin as it inflates, without tangling the shroud lines.

Chapter 10

Nosecones

There are two theories to nosecone design:
1. Make it as heavy as possible.
2. Make it as light as possible.

The reasoning behind the first theory is stability—by adding weight to the nose of the rocket, you move the center of gravity forward, increasing the rocket's stability. This is the "quick–and–easy" way to build a rocket, but it has a major downfall—you won't get over a few seconds aloft, because the rocket is simply too heavy.

Since you've already read this far into the handbook, you're obviously not looking for the "quick–and–easy" way to build anything. Instead, we'll look at making nosecones light and strong.

10.1 Materials

Selecting the right material is the key to building a light nosecone. Pieces from plastic bottles tend to work well, as long as you do not use the nozzle section or the base of the bottle—these are the heaviest sections (See Appendix C for more information on bottle weights).

If you decide to use part of a 2 liter bottle as a nosecone, be sure to cut off the top 4 cm of the nozzle. To cover the hole, you

can make a small cone out of the mid-section of a bottle. Simply take a piece of plastic from a bottle, roll it into a conical shape, and attach it with glue or packaging tape.

To make your nosecone even lighter, thoroughly sand it with 100 grit sandpaper. (Remember: **Sanding on the pressurized bottle is not allowed**, but you can do whatever you want to nosecones and other parts) You can typically reduce the weight of the cone by 30% to 50% by sanding. After doing this, the plastic will become very rough—use a lighter grain of sandpaper (500 to 1500 grit) to make the plastic smooth.

10.2 Aerodynamics

The nosecone is the most important part of a rocket's aerodynamics. It is critical that the nosecone is rigid, because the rocket will experience 80 to 100 MPH of wind as it is launched—paper or other weak materials will not help to deflect the wind under these speeds.

Shape of the nosecone is also important to reduce drag. The best way to test nosecone shape is using a wind tunnel, but we will not cover wind tunnels in the handbook. More information, including plans to build your own wind tunnel, can be found on the Internet.

Part III

Mathematical Calculations

Chapter 11

Dome Parachute Calculations

This chapter on dome parachute calculations is here as an introduction to constructing 3-dimensional parachutes. The algorithms in the next chapter, *Elliptical Parachute Algorithms*, can calculate both elliptical and dome parachutes, but those are far more complex and much harder to learn. The calculations in this chapter are much simpler, and will work well enough for most students.

In the Chapter 7, we looked at how to construct elliptical and dome parachutes—they are made up of multiple panels in the shape of spherical triangles. The purpose of this chapter is to calculate the shape of these spherical triangles. In this chapter, we will calculate an 8–panel, 100 cm diameter dome parachute.

First, we look at our parachute through its vertical cross-section—a semi-circle. The first step in calculating our panel is find its length. This is easy enough, since the panel occupies half of our semi-circle. Thus, the panel length, P_l, is

$$P_l = \frac{\pi d}{4}$$

where d is the diameter of of the parachute. For our parachute, this formula gives us a panel length of approximately 78.5 cm.

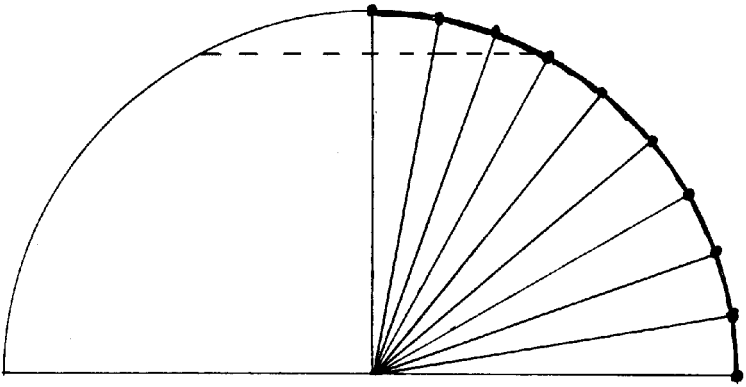


Figure 11.1: Equally-spaced points on the vertical cross-section of a parachute

Next, we must calculate some equally-spaced points along one side of the semi-circle. The number of points you calculate depend on how accurate you want your panel to be. Typically 10 to 20 points is sufficient. The purpose of these points is to serve as reference points for the rest of our calculations.

To calculate these points, first divide 90° by one less than the number of points you wish to calculate. We will use 10 points, giving us a result of 10°. This means that our points are at multiples of 10°: 0°, 10°, 20°, ...80°, 90°. These angles are measured from the origin of the semi-circle.

Since these points are equally-spaced along our horizontal cross-section, they will also be equally-spaced along our final panel. The distance between each point can be calculated by taking the panel length, P_l, and dividing it by the number of points minus one. For our parachute, the distance between points is $78.5/(10-1) \approx 8.7$ cm. The y-values of our parachute are multiples of this number: 0.0, 8.7, 17.4, ...69.8, 78.5 cm[1].

[1]Notice that 78.5 is not a multiple of 8.7. This is due to a rounding error—you must actually use the full decimal value, 8.7222..., when calculating your y-values.

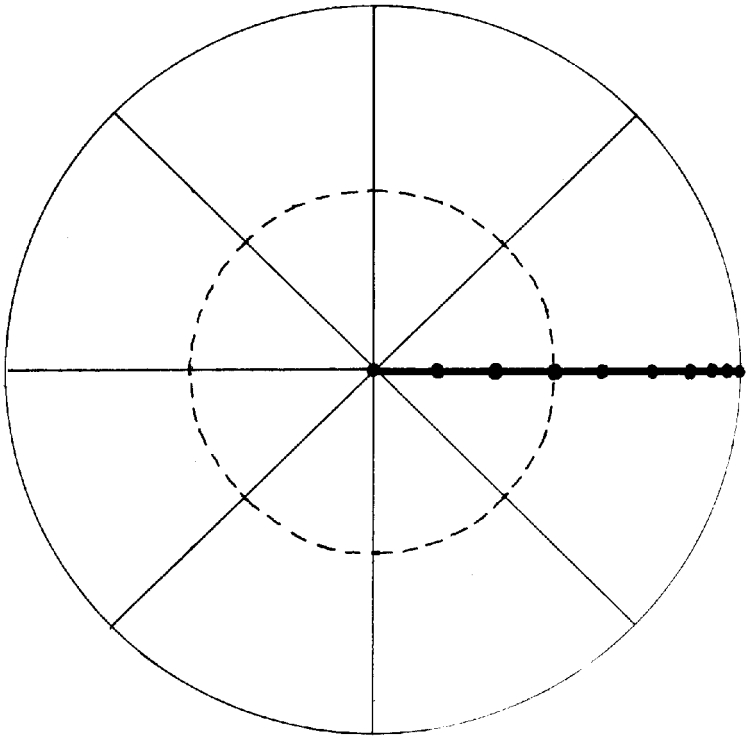


Figure 11.2: Equally-spaced points along the horizontal cross-section of a parachute

Next, we will look at the horizontal cross-section through each of these points. The parachute, like the skin of an onion, forms circular rings when it is sliced horizontally. Also, these rings have an important property: they pass through each panel of the parachute equally.

As far as calculating these rings, we must go back to the vertical cross-section to first find their diameter. The formula uses basic trigonometry, so its dervitation will not be shown here:

$$d_{\text{ring}} = d \cos \theta$$

d is the diameter of the parachute. θ is one of the angles calculated above.

We must calculate the diameter for every one of the equally-spaced points shown above. For our 100 cm parachute, you should get the following values for the diameters: 100.0, 98.5, 94.0, ... 17.4, 0.0 cm.

We can calculate the circumference of each of these circles using the formula, $c_{\text{ring}} = \pi d_{\text{ring}}$, then divide each of these values by the number of panels to get the length of the arc passing through one panel. For our parachute, you should get the following values: 39.2, 38.7, 36.9, ... 6.8, 0.0 cm.

We're almost done! These arcs, when mapped our 2-dimensional panel, will become straight lines. Our panel is symmetrical over the y-axis, so we can calculate our x-values by dividing the arc lengths by two. Pairing these with the y-values calculated earlier gives us our final panel coordinates: ($\pm$19.6, 0.0), ($\pm$19.3, 8.7), ($\pm$18.5, 17.4), ... ($\pm$3.4, 69.8), ($\pm$0.0, 78.5).

Chapter 12

Elliptical Parachute Algorithms

We showed how to calculate points for a dome parachute in the previous chapter, but how can you calculate points for an elliptical parachute? The technique is very similar: we make a parachute panel by first calculating the points on a vertical cross-section of the parachute, which forms the top half of an ellipse (hence the name "elliptical parachute"). Once we have the points on a vertical cross-section, we take a horizontal cross-section of the parachute at each of the points we calculated. Since a horizontal cross-section is a circle, the radius is the distance from the point to the y-axis on the vertical cross-section. And once we have the circle, we can find the circumference, and divide the circumference by the number of panels to find the width of the panel at that point.

The trick is in calculating the equidistant points around the ellipse. The equations for an ellipse are covered in any good math book, but for this application, we must go a step further. There is no exact, mathematical method for calculating equally-spaced points on an ellipse, so we must develop an algorithm to estimate the coordinates.

12.1 Tangent Points Algorithm

The Tangent Points Algorithm is a recursive formula for calculating equidistant points on an ellipse by using derivatives to determine the slope of the tangent line through any point. It requires a basic knowledge of calculus. See the next section for another algorithm, although not as accurate, that does not require any calculus.

Since these points are equidistant, we can refer to the distance between them as a constant[1], z. Once we calculate our z value and have one point on the ellipse, we can estimate the point adjacient to it by constructing the tangent through the point, with a length of z. Mathematically, this cannot actually be a point on the ellipse, since tangents only touch one point, but if we calculate enough points, the points will fit the ellipse close enough for our purposes.

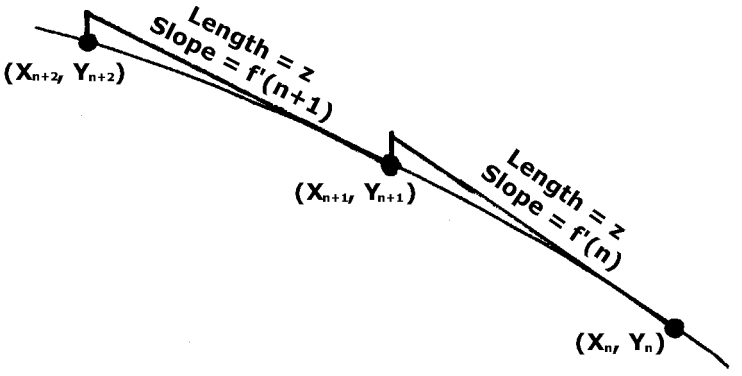


Figure 12.1: Estimating equidistant points using tangent lines

[1]The constant, z, is different for every parachute.

Let's start by looking at the variables that are inputs:

Variable	Description	Unit	Range
d	Diameter	cm	$d > 0$
h	Height	cm	$h > 0$
P_n	Number of Panels		$P_n \geq 3$
o	Overhang	cm	$o \geq 0$
p	Number of Points		$p \geq 3$
s	Seam Width	cm	$s \geq 0$
f	Precision Factor		$2.0 \leq f \leq 10.0$
M_t	Material Thickness	cm	$M_t > 0$
M_d	Material Density	$\mathrm{g/cm^3}$	$M_d > 0$

Next, well calculate some other variables:

Var.	Description	Unit	Formula
r	Radius	cm	$r = \frac{d}{2}$
P_l	Panel Length	cm	$P_l = \left(\frac{\pi}{4}\right)\left(3[r+h] - \sqrt{(r+3h)(h+3r)}\right)$
F	Precision		$F = 10^f$
c	Number of Calculated Points		$c = F \cdot (p-1) + 1$
z	Distance Between Points	cm	$z = \frac{P_l}{c}$

Radius should be self-explanitory.

Panel Length is $1/4^{\text{th}}$ the circumference of the ellipse[2]. The formula is based upon Ramanujan's formula for the circumference of an ellipse.

Precision, and its cousin, Precision Factor, have been arbitrary values up until this point, but they become very important when determining the number of points to calculate. As stated earlier, we actually calculate many more points than we use, to make the points fit the ellipse closer. The multiple which we use

[2]Be careful not to confuse the circumference of the ellipse with the circumference of the opening.

is called Precision, and Precision Factor is simply a logarithmic scale of Precision. These variables should be set as high as possible, considering the speed of your computer, to get an accurate computation. The higher these numbers are, the more accurate the panel will be, but it will take longer to calculate.

And finally, we calculate our z, which tells us how long we need to make our tangents.

Before we go any further, we must explain a bit of the notation that will be used in the next sections. The lowercase letters x and y denote coordinates on the vertical cross-section of the parachute, and the uppercase letters X and Y denote the x- and y-coordinates on the pattern for the panel. Points that are being calculated are denoted as (x_n, y_n), and this point on the vertical cross-section corresponds to the point (X_n, Y_n) on the panel. The point adjacient to (x_n, y_n) on the ellipse, which would be located above this point on the panel, is denoted (x_{n+1}, y_{n+1}). Also, the notation $(x_n, f(x_n))$ is identical to (x_n, y_n), because we can solve the equation for an ellipse in terms of y to get a function, $f(x_n)$ to find the y-value at the x-value of x_n.

Next, we will do some manipulation to our equation for an ellipse, to get it in the forms that we need for our algorithm.

The basic equation for an ellipse is $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, but in our case, a is the radius of the parachute and b is the height, so we will use the equation $\frac{x^2}{r^2} + \frac{y^2}{h^2} = 1$ instead.

Solving for y yields: $f(x) = y = h\sqrt{1 - \frac{x^2}{r^2}}$ (Actually the left side should have a $\pm$ sign, but we do not include it, because we are only concerned with the positive side of the ellipse)

And next, we take the derivative using implicit differentiation:

$$\begin{aligned}
\frac{x^2}{r^2} + \frac{y^2}{h^2} &= 1 \\
\left(\frac{1}{r^2}\right) x^2 + \left(\frac{1}{h^2}\right) y^2 &= 1 && \text{(Note}^3\text{)} \\
\frac{d}{dx}\left[\left(\frac{1}{r^2}\right) x^2 + \left(\frac{1}{h^2}\right) y^2\right] &= \frac{d}{dx}[1] && \text{Implicit Differentiation} \\
\left(\frac{1}{r^2}\right) 2x + \left(\frac{1}{h^2}\right) 2y \left(\frac{dy}{dx}\right) &= 0 \\
\frac{2y\left(\frac{dy}{dx}\right)}{b^2} &= -\frac{2x}{r^2} \\
\frac{dy}{dx} &= -\frac{h^2 x}{r^2 y} \\
\frac{dy}{dx} &= -\frac{h^2 x}{r^2 h\sqrt{1 - \frac{x^2}{r^2}}} && \text{Substitute for } y \\
f'(x) = \frac{dy}{dx} &= -\frac{hx}{r^2\sqrt{1 - \frac{x^2}{r^2}}}
\end{aligned}$$

We could simplyify the derivative further by rationalizing the denominator, but the current formula is faster when calculated on a computer, so we will leave it here.

Next, given any point $(x_n, f(x_n))$, we will calculate the point $(x_{n+1}, f(x_{n+1}))$, which is z cm away from $(x_n, f(x_n))$.

Here is the only flaw in algorithm, which is why it is only an approximation of the ellipse: We assume that the ellipse is a straight line passing through the two points, and thus, $f'(x_n) = f'(x_{n+1})$. This is obviously not true, because an ellipse does not consist of straight lines, but since any two adjacient points are

[3] $\left(\frac{1}{r^2}\right)$ and $\left(\frac{1}{h^2}\right)$ are treated as constants for the parachute

extremely close together, we can make this assumption without causing too much error in the results. (We will actually calculate this error later, just to make sure)

$$\begin{aligned}
f'(x_n) &= \frac{\Delta y}{\Delta x} && \text{Assumption} \\
\Delta x^2 + \Delta y^2 &= z^2 && \text{Pythagorean Theorem} \\
\Delta y &= \sqrt{z^2 - \Delta x^2} \\
f'(x_n) &= \frac{\sqrt{z^2 - \Delta x^2}}{\Delta x} && \text{Substitution} \\
\Delta x \cdot f'(x_n) &= \sqrt{z^2 - \Delta x^2} \\
(\Delta x \cdot f'(x_n))^2 &= z^2 - \Delta x^2 \\
\Delta x^2 (f'(x)^2 + 1) &= z^2 \\
\Delta x^2 &= \frac{z^2}{f'(x)^2 + 1} \\
\Delta x &= \frac{z}{\sqrt{f'(x)^2 + 1}}
\end{aligned}$$

We substitute our $f'(x)$ from the section above:

$$\Delta x = \frac{z}{\sqrt{\left[\frac{h \cdot x_n}{r^2\sqrt{1 - \frac{(x_n)^2}{r^2}}}\right]^2 + 1}}$$

Since $x_{n+1} = x_n - \Delta x$, substitution yields:

$$x_{n+1} = x_n - \frac{z}{\sqrt{\left[\frac{hx}{r^2\sqrt{1 - \frac{(x_n)^2}{r^2}}}\right]^2 + 1}}$$

And now we have our recursive formula for finding an adjacient point on the ellipse!

Now let's put out recursive formula to use. But first, more notation: p_n denotes the n^{th} point on the vertical cross-section, while P_n denotes the n^{th} point on the panel. Mathematically, this could be written as $p_n = (x_n, y_n)$ and $P_n = (X_n, Y_n)$. Since we are calculating more points than we are actually going to use, we also need a way to denote the calculated points. These we will call c_n.

Mapping calculated points (c_n's) to vertical cross-section points (p_n's) is fairly easy. The first calculated point maps to the first vertical cross-section point ($c_1 = p_1$). Then, we ingore the next few points, as determined by the precision. For instance, if precision (F) was 10, then we are calculating 10 points for every one that are used, thus points c_2 through c_{10} are dropped, and the next point we use is c_{11}, which would map to p_2. The mathematical formula for this is:

$$p_n = c_{F(n-1)+1}$$

(Note the similarity to the formula for the number of calculated points, c)

We know the first and last points on our ellipse, p_1 and p_p (which map to c_1 and c_c):

$$p_1 = c_1 = (r, 0)$$

$$p_p = c_c = (0, h)$$

Now that we have $c_1 = (r, 0)$, giving us $x_1 = r$, we can calculate all of the points in between c_1 and c_c using our recursive formula[4].

[4]Our recursive formula only gives us x-values, but we could calculate the y-values using our formula, $f(x)$, which is the equation for an ellipse solved in terms of y. As you will see later, we do not need to do this, because we only use the x-values of the coordinates.

Since we have calculated a value for the second-to-last point $(c_c - 1)$, we might as well give our recurisive formula one more run, and calculate c_c again, even though we know its value. We do this to establish how far off our estimates are, by calculating a percent error value. If the percent error is high, this would indicate that we should increase our precision factor and run the program all over again. Heres the formula for percent error:

$$\%_{\text{error}} = \frac{|x_c - r|}{r} \cdot 100$$

We have calculated our points and pulled out only the ones we will use, so next we must convert our vertical cross-section points to actual points on the parachute panel. As stated before, we do this by taking the horizontal cross-section through the point on the parachute, which is a circle, which happens to have the same radius as a x-value in p_n. The formulas should be simple enough to prove on your own, so here they are:

$$X_n = \pm\frac{2\pi x_n}{P_n}$$

$$Y_n = \frac{P_l(n-1)}{p-1}$$

We now can calculate the coordinates for the curved part of the panel for any elliptical parachute! Although that's the meat of the section, there are still some more calculations left, to take full advantage of the parachute algorithm. The overhang formulas look fairly complicated, but they can be derived using basic geometry, so their proofs will not be included here.

Variable	Description	Unit	Formula
P_w	Max. Panel Width	cm	$P_w = 2X_1$
O_r	Overhang Radius	cm	$O_r = \frac{\frac{P_w^2}{4o} + o}{2}$
O_a	Overhang Angle	rad.	$O_a = 2\arcsin(\frac{P_w}{2O_r})$
O_v	Overhang Vertex	(x, y)	$O_v = (0, O_r - o)$
A_{overhang}	Overhang Area	cm^2	$= \frac{(O_a \cdot O_r^2) - (P_w[O_r - o])}{2}$
A_{opening}	Opening Area	cm^2	$A_{\text{opening}} = \pi r^2$
V_{inner}	Inner Volume	cm^3	$V_{\text{inner}} = \frac{2\pi}{3} \cdot hr^2$
A_{panel}	Panel Area	cm^2	$A_{\text{panel}} = \sum_{n=2}^{p}(X_n + X_{n-1}) \left(\frac{P_l}{p-1}\right)$
A_{surface}	Surface Area	cm^2	$A_{\text{surface}} = A_{\text{panel}} \cdot P_n$
S_l	Seam Length	cm	$= \sum_{n=2}^{p} \sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2}$
A_{seam}	Seam Area	cm^2	$A_{\text{seam}} = S_l s$
A_{total}	Total Area	cm^2	$= (A_{\text{panel}} + A_{\text{overhang}} + 2A_{\text{seam}}) \cdot P_n$
V_{folded}	Volume Folded	cm^3	$V_{\text{folded}} = A_{\text{total}} \cdot M_t$
m	Mass	g	$m = V_{\text{folded}} \cdot M_d$

12.2 Angle Repetition Algorithm

The Angle Repetition Algorithm is another algorithm for calculating equidistant points on an ellipse. It requires a significantly greater amount of processing time, and it is not as accurate, but it can be done without using calculus.

The algorithm works similar to the Tangent Points Algorithm, but instead of using derivatives to calculate points, it uses a ray, drawn from the center of the ellipse. First, the approximate point distance is calculated. Then, the slope of the ray is gradually increased, until the point of intersection of the ray and the ellipse is the correct distance from the previous point.

Chapter 13

Simulators

Simulators are the most useful tools for designing rockets. Algorithms for stability and parachutes were discussed in previous chapters, so this chapter will look at simulating the flight of the rocket to predict factors such as flight time, height, and acceleration.

Simulators give only an estimation of a flight. The actual height, time aloft, and other characteristcs can vary tremendously from the simulated values, sometimes by 50% or more. Although outside factors make the actual flight unpredictable, this is what makes simulators so important. Because there are so many uncontrollable factors, simulators are often the only method of comparing modifications to rockets. (For example: Which rocket stays aloft longer, a 150 g rocket with an 80 cm parachute, or a 200 g rocket with a 100 cm parachute?) To answer this question without a simulator, you would have to build two different rockets, two different parachutes, and measure the time aloft on numerous launches of each to get accurate enough averages to determine the answer. Not only does this take days to do, but it is often impossible, because rockets often have a short lifespan of only a few launches. As soon as one of the two rockets fails, and crashes to the ground, you have to build a new rocket and start testing all over again. Simulators make this task

much easier—simply punch in a few numbers, and the simulator will compare the two rockets.

13.1 Notation

Because of the number of different constants, variables, and functions used in the bottle rocket simulator, notation becomes very difficult. For the purpose of clarity, the following naming conventions are used throughout this chapter:

a denotes acceleration	A denotes Area
d denotes diameter	D denotes Density
m denotes mass in kg	M denotes Molar Mass (kg/mol)
t denotes time	T denotes Temperature
v denotes velocity	V denotes Volume

In addition, standard units of measure are used for variables, constants, and functions. This may look awkward when doing computations (For instance, the diameter of the nozzle will be measured in, yes, *meters*!), but it makes the rest of the formulas far less complicated. The following units of measure are assumed for *all* values:

Acceleration	m/s^2
Area	m^2
Density	kg/m^3
Force	newtons
Length (Height, Diameter, etc.)	meters
Mass	kilograms
Molar Mass	kg/mol
Pressure	Pascals
Temperature	Kelvin
Time	seconds
Velocity	m/s
Volume	m^3

Finally, we must make a distinction between the air on the inside and outside of the bottle, because they have different pressures

and densities, which is important in our calculations. The air inside the bottle will be referred to as *air*, while the air on the outside will be reffered to as *atmosphere*.

13.2 Constants, Variables, and Functions

It is important to understand how constants, variables, and functions are used in this simulator.

A constant (such as π) is a number that *never* changes. Constants are used to determine the relationship between different units and measurements, such as the ideal gas constant, K_{gas}, which relates the pressure, volume, and temperature of a gas.

A variable (such as diameter) is a number that changes with the rocket. The value of a variable can be different for each rocket, but the value of the variable stays the same throughout the entire flight of a rocket.

Functions (such as velocity) are used for values that are constantly changing throughout the flight of a rocket. These values are written as a function of time, t, ($f(t)$). The variable t represents the time, in seconds, since the rocket is launched (when the locking mechanism is released, not when it comes off the launch pad).

13.3 Acceleration, Velocity, and Height

Acceleration, velocity, and height are the three most important functions in the simulator and are written as $a(t)$, $v(t)$, and $h(t)$, respectively. Determining the values of these three functions is the purpose of a simulator. The graphs of these functions are often plotted, to determine information such as maximum height, maximum acceleration, impact velocity, time of apogee, and time aloft.

These three functions are related by integration. Integrating $a(t)$ yields $v(t)$, and integrating $v(t)$ yields $h(t)$. Thus, if we can

calculate the value of one function, we can determine the values of the other two.

We will determine the value of the acceleration function, $a(t)$, using Newton's law,

$$\text{Force} = \text{Mass} \times \text{Acceleration}$$

By rearranging to get the acceleration function by itself, we get:

$$a(t) = \frac{F_{\text{sum}}(t)}{m(t)}$$

$F_{\text{sum}}(t)$ is the sum of the different forces that act upon the rocket. We can calculate it by adding together all the different forces that our simulator takes into consideration:

$$F_{\text{sum}}(t) = F_{\text{grav}}(t) + F_{\text{rod}}(t) + F_{\text{drag}}(t) + F_{\text{prop}}(t) + F_{\text{par}}(t)$$

$m(t)$ is the function for the total mass of the rocket (including water) at any given time. We will calculate this function in a later section.

13.4 Computer Integration

The acceleration formula has not gotten extremely complex yet, but over the next ten pages, it will. Obviously, we don't want to do all of this calculus by hand, so now is a good time to explain how to integrate a formula like this one using a computer.

To integrate a complex function, like the acceleration function presented in this chapter, the best we can do is to find an approximation of the integral—the formula is far too complex to get an exact value. We can approximate this estimate using the rectangle method[1].

[1] A better approximation formula for integrals, such as the Trapezoidal Rule or Simpson's Rule, can be used for a more efficient simulator

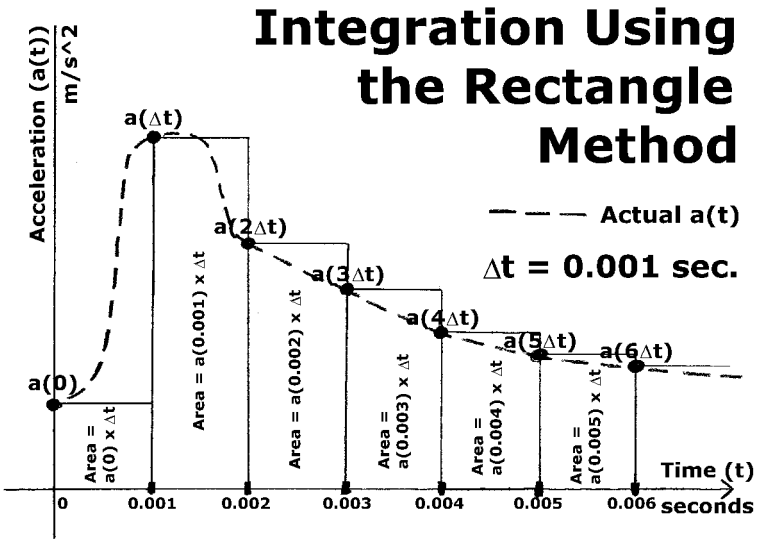


Figure 13.1: Integration Using the Rectangle Method

Instead of letting Δt equal zero and finding the limit, like we would do if we were finding an exact value, we set it to a value extremely close to zero, like 0.001. (Remember, Δt is a measure of time, thus its unit of measure is seconds. 0.001 seconds equals one millisecond.)

We start off with $t = 0$, and compute our value of $a(t)$. We will next recalculate $a(t)$ at $t = \Delta t$, so we will assume that the value of $a(t)$ stays the same from 0 to Δt. If we plot these values on a graph, and draw a rectangle extending to the x-axis, we have a rectangle of area:

$$A(0) = a(0) \cdot \Delta t$$

We increment our time, t, by Δt and repeat this process. The sum of all of these rectangles should make a close approximation of the integral of $a(t)$:

$$\int_0^{t_{\text{impact}}} a(t)\ dt \approx \sum_{t=0}^{(t_{\text{impact}}/\Delta t)} (a(t \cdot \Delta t) \cdot \Delta t)$$

Notice that we integrate from 0 to t_{impact}. Where did t_{impact} come from? When we begin our simulation, we have no clue how long the rocket's flight time will last. t_{impact} is not a real value—it just tells us to start calculating values, and integrate until $h(t)$ hits the ground.

We can integrate $v(t)$ the same way to get $h(t)$:

$$\int_0^{t_{\text{impact}}} v(t)\ dt \approx \sum_{t=0}^{(t_{\text{impact}}/\Delta t)} (v(t \cdot \Delta t) \cdot \Delta t)$$

You will also notice that some of the formulas in this section require the value from a function that we cannot calculate, until we calculate the first formula (e.g. $v(t)$ and $F_{\text{drag}}(t)$). This is another benefit of integration on a computer—we can simply use the last calculated value of the function (usually $f(t - \Delta t)$) as an approximation of the actual value that we need.

13.5 Calculations

13.5.1 Launch Rod

Although the launch rod may seem to be of little importance, it is actually critical to a simulator and to the flight of a rocket. Even on launchers with only small rubber fitting as a launch

rod (usually with a length of 2 cm or less), the rocket will reach a speed of 10 MPH before it ever leaves the launch rod. On launchers that use a pipe or other longer launch rod, this speed is greater, and the launch rod is even more critical.

The following are input values related to the launch rod:

Variable	Description	Unit
d_{rod}	Diameter of Launch Rod[2]	m
l_{rod}	Length of Launch Rod	m

Since we will need the area of the top of the launch rod for further calculations, we will first find the radius of the launch rod, r_{rod}, and then calculate the perpendicular surface area of the launch rod, A_{rod}:

$$\begin{aligned} r_{\text{rod}} &= \frac{d_{\text{rod}}}{2} \\ A_{\text{rod}} &= \pi(r_{\text{rod}})^2 \end{aligned}$$

We will also do the same for R_{nozzle} and A_{nozzle}:

$$\begin{aligned} r_{\text{nozzle}} &= \frac{d_{\text{nozzle}}}{2} \\ A_{\text{nozzle}} &= \pi(r_{\text{nozzle}})^2 \end{aligned}$$

As the rocket goes up as it is coming off the launch pad, the amount of the launch rod inside the bottle decreases. Next, we will calculate two functions, $l_{\text{rodB}}(t)$ and $V_{\text{rodB}}(t)$, to determine the length and volume of the launch rod remaining inside the bottle:

$$\begin{aligned} l_{\text{rodB}}(t) &= l_{\text{rod}} - h(t) \\ V_{\text{rodB}}(t) &= l_{\text{rodB}}(t) \cdot A_{\text{rod}} \end{aligned}$$

[2]The diameter of the launch rod must be the same as the nozzle of the bottle, therefore the value of d_{rod} may be referred to as d_{nozzle} when it is used to calculate water flow out of the nozzle.

13.5.2 Pressurized Bottle, Water, and Air

There are three things inside the pressurized bottle during the initial launch: water, launch rod, and air. Now that we have calculated the volume of launch rod, we must calculate the water and air.

The following variables are inputs for our simulator:

Variable	Description	Unit
V	Bottle Volume	m^3
d	Bottle Diameter	m
$V_{water}(0)$	Initial Water Volume	m^3
$P_{air}(0)$	Initial Air Pressure	Pa
C_d	Drag Coefficient of Rocket	C_d

$V_{water}(0)$ is the initial value of the function $V_{water}(t)$. We will show how to calculate $V_{water}(t)$ for values of t other than zero in the section, *Propulsive Forces.*

We now have the volume of water and launch rod inside the bottle, therefore the rest must be air. Let $V_{air}(t)$ represent the volume of air inside the bottle (in m^3):

$$V_{air}(t) = V - V_{water}(t) - V_{rodB}(t)$$

Boyle's Law states that the pressure and volume of a gas vary inversely. Thus, as the volume of air inside the bottle increases, due to the water and launch rod leaving, the pressure of the air decreases proportionally. Using Boyle's Law, $P_1V_1 = P_2V_2$, we get the formula for the air pressure inside the bottle, $P_{air}(t)$:

$$P_{air}(t) = \frac{P_{air}(0) \cdot V_{air}(0)}{V_{air}(t)}$$

13.5.3 Preliminary Propulsive Calculations

The next step involves calculating the height of the water inside the bottle and the surface area of the top of the water. We need these values to calculate the propulsion of water out of the bottle.

This is one place we will make a large simplification. We could actually measure the diameter of the bottle at many different heights to input the bottle's shape into the simulator, but instead, we will simply assume that the bottle is a perfect cylinder, with a hole the size of the nozzle in the bottom. For 2-liter bottles, this simplification should not make much of a difference. For bottles with a longer neck, this may make more of a difference. Also, by working it out the long way, and measuring actual diameters, we could make a simulator that compares the propulsion of different shapes of bottles. This will not be covered here.

For our cylindrical bottle, the perpendicular area of the bottle, A_{perp}, can be found using the formula:

$$A_{\text{perp}} = \pi r^2$$

We also have a function, $A_{\text{surf}}(t)$, which is the surface area of the top of the volume of water indicated by $V_{\text{water}}(t)$. For our cylindrical bottle, this value will always be the same as the perpendicular area of our bottle:

$$A_{\text{surf}}(t) = A_{\text{perp}}$$

Finally, we must find the height of the water level, $h_{\text{water}}(t)$. For our cylindrical bottle, this is easy:

$$h_{\text{bottle}} = \frac{V_{\text{water}}(t)}{A_{\text{surf}}(t)}$$

13.5.4 Mass

Mass is another important factor in rocket design. A simulator must also consider the changing mass of the rocket, due to the propulsion of the water.

Our simulator will have three more input variables:

Variable	Description	Standard Value	Unit
m_{empty}	Empty Mass		kg
D_{water}	Density of Water	1000	kg/m^3
a_{grav}	Acceleration of Gravity	-9.806	m/s^2

D_{water} is typically 1000 kg/m^3, but by using a variable, we can test the effect of different substances as propellants. a_{grav} is similar—here on Earth, the value does not change, but just in case you wanted to see what a rocket would do under the moon's gravity...

To calculate the changing mass, we first find the mass of water, $m_{\text{water}}(t)$:

$$m_{\text{water}}(t) = V_{\text{water}}(t) \cdot D_{\text{water}}$$

We simply add the empty mass of the rocket to mass of the water to get the total mass, $m(t)$:

$$m(t) = m + m_{\text{water}}(t)$$

13.5.5 Air and Atmosphere

The next thing our simulator will need is the density of air and atmosphere. (Remember the difference: *air* is inside the rocket; *atmosphere* is outside.)

Calculating the density of air and atmosphere will require five more inputs:

Variable	Description	Standard Value	Unit
v_{updraft}	Updraft Velocity	0	m/s
P_{atm}	Atmospheric Pressure	101325	Pa
T_{atm}	Atmospheric Temperature		K
T_{air}	Air Temperature		K
M_{atm}	Molar Mass of Atmosphere	0.029	kg/mol
M_{air}	Molar Mass of Air	0.029	kg/mol

Updraft velocity is a constant, that in later calculations, will be added to the rocket's velocity to determine the relative wind. A positive value will simulate an updraft resulting from a thermal or a hill. Typical updrafts range from 0 to 0.5 m/s.

Notice that the air temperature and atmosphere temperature are input as separate values. Shouldn't they be the same since the air we pump inside comes directly from the air outside? Not exactly. On most launchers, the air comes out of the launch rod and bubbles up through the water. When this occurs, there is a heat exchange between the air and the water. The change in temperature is small, so it has little effect on the overall launch, but this gives you the option of experimenting with heated or chilled air inside the rocket.

Another important thing to notice is that the molar mass of air is input input separately from atmosphere. The typical value for the air we breath is 0.029 kg/mol, but many bottle rocket launchers are equipped with air tanks, and often, nitrogen, oxygen, or another gas is used instead of ordinary air. The type of gas used to pressurize the rocket *does* make a difference, so here are some values of common gases:

Gas	Molar Mass
Helium (He)	0.004 kg/mol
Nitrogen (N_2)	0.028 kg/mol
Air	0.029 kg/mol
Oxygen (O_2)	0.032 kg/mol
Carbon Dioxide (CO_2)	0.044 kg/mol

We will make another assumption: air, or whatever other gas we are using, is an ideal gas. This allows us to use the Ideal Gas Law,

$$PV = nRT$$

where P represents pressure, V represents volume, n represents the number of moles of gas, R is a gas constant, and T is the temperature in Kelvin. Since:

$$\begin{aligned} \text{Number of Moles} &= \frac{\text{Mass}}{\text{Molar Mass}} \\ n &= \frac{m}{M} \end{aligned}$$

we can rewrite the equation as

$$\begin{aligned} PV &= \frac{mRT}{M} \\ MPV &= mRT \\ \frac{PM}{RT} &= \frac{m}{V} \end{aligned}$$

Since:

$$\begin{aligned} \frac{\text{Mass}}{\text{Volume}} &= \text{Density} \\ \frac{m}{V} &= D \end{aligned}$$

we can substitute m/V for D, yielding:

$$D = \frac{P \cdot M}{R \cdot T}$$

With this variation of the Ideal Gas Law, we get the following two equations for the denstity of air, D_{air}, and the density of atmosphere, D_{atm}:

$$\begin{aligned} D_{\text{air}} &= \frac{P_{\text{air}} \cdot M_{\text{air}}}{K_{\text{gas}} \cdot T_{\text{air}}} \\ D_{\text{atm}} &= \frac{P_{\text{atm}} \cdot M_{\text{atm}}}{K_{\text{gas}} \cdot T_{\text{atm}}} \end{aligned}$$

($K_{\text{gas}} \approx 8.31441\ \text{Pa} \cdot \text{m}^3/\text{mol} \cdot \text{K}$)

13.5.6 Parachute

The final set of calculations involves parachutes. The following values are needed as inputs:

Variable	Description	Unit
n_{par}	Number of Parachutes	
A_{par}	Surface Area of Each Parachute	m^2
C_{pd}	Parachute Drag Coefficient	C_d
T_{deploy}	Length of Time to Fully Deploy	sec.
K_{par}	Parachute Deploy Constant	

All of the values should be self-explanatory, except for one: the parachute deploy constant, K_{par}. This is a value used to deploy the parachute exponentially. Without an exponential deploy, the parachute instantly being fully deployed would cause a huge jump in the acceleration graph, causing G-forces that would rip the rocket apart. A value of 10 is normally used for K_{par}. This value has no logical meaning and little scientific basis, but it seems to work well. Lower values create a smoother deploy, while higher values will create a rougher one.

To calculate our parachute's deploy, we need to keep track of our apogee time, which we will record as t_{apogee}. So how do we know when the rocket is at apogee? The First Derivative Test! Whenever our $v(t)$ value goes from positive to negative, our rocket has passed apogee. At this time, we store the current value of the elapsed time, t, as t_{apogee}.

After apogee, we can start calculating the percent deployed of our parachute, $\%_{\text{deployed}}(t)$:

$$\%_{\text{deployed}}(t) = \left(\frac{t - t_{\text{apogee}}}{t_{\text{deploy}}} \right)^{K_{\text{par}}} \times 100$$

Like K_{par}, our formula for $\%_{\text{deployed}}(t)$ just generates an arbitrary $y = x^k$ graph that seems to make a smooth parachute deploy.

From $\%_{\text{deployed}}(t)$, we calculate the total area of parachute that has been deployed, $A_{\text{parD}}(t)$:

$$A_{\text{parD}}(t) = n_{\text{par}} \cdot A_{\text{par}} \cdot \%_{\text{deployed}}(t)$$

13.6 Forces

13.6.1 Gravity

With all of our overhead calculations completed, we can begin calculating the actual forces that act on the rocket. First, we will look at gravity.

Remember the $F = ma$ equation from the beginning of the chapter? We will use this same equation to calculate the force of gravity:

$$F_{\text{grav}}(t) = m(t) \cdot a_{\text{grav}}$$

13.6.2 Launch Rod Reaction Force

The launch rod reaction force is the force that gives the rocket its initial "push" off the launch pad. It is actually two forces in one: the force of the air inside the bottle pushing on the launch rod minus the force of the atmosphere which is working against the launch rod reaction force.

We can calculate these forces by taking the pressure inside the bottle and multiplying it times the area of the surface which it pushes against:

$$\begin{aligned} F_{\text{air}}(t) &= P_{\text{air}}(t) \cdot A_{\text{rod}} \\ F_{\text{atm}}(t) &= P_{\text{atm}} \cdot A_{\text{rod}} \end{aligned}$$

Subtracting these forces yields:

$$\begin{aligned} F_{\text{rod}}(t) &= F_{\text{air}}(t) - F_{\text{atm}}(t) \\ F_{\text{rod}}(t) &= (P_{\text{air}}(t) \cdot A_{\text{rod}}) - (P_{\text{atm}} \cdot A_{\text{rod}}) \\ F_{\text{rod}}(t) &= A_{\text{rod}}(P_{\text{air}}(t) - P_{\text{atm}}) \end{aligned}$$

13.6.3 Wind Resistance

Since there is no exact formula to calculate the wind resistance of an object moving through the air, scientists approximate this force using a drag coefficient, or C_d. The only accurate way to determine a drag coefficient is by experimentation in a wind tunnel, but drag coefficients for bottle rockets are typically in the 0.2 to 0.5 range. Here is the formula for the wind resistance of the rocket:

$$F_{\text{drag}}(t) = \pm\frac{C_d \cdot D_{\text{atm}} \cdot A_{\text{perp}} \cdot [v(t) + v_{\text{updraft}}]^2}{2}$$

Wind resistance is typically a downward force, but you must look at the velocity of the relative wind, $v(t) + v_{\text{updraft}}$, to determine whether the force is truly positive or negative.

13.6.4 Propulsive Forces

The propulsive force of the rocket is caused by the water that pushed through the nozzle by the pressurized air. Remember the law, "For every action, there is an equal and opposite reaction?" In this case, the action is pushing water out of the nozzle, and the reaction is the propulsive force that makes the rocket go up.

First, we must realize that the water at the water's surface is moving at a different velocity that the water at the nozzle. Second, we must show that at and point in the water, there is an inverse relationship between the velocity of the water and the area of the bottle's horizontal cross-section.

Let's assume that at a given point in time, the velocity of surface of the water is $v_{\text{surf}}(t)$ meters per second. Therefore, in a period of time, Δt, the water level will drop h_{surf} meters, where

$$\begin{aligned} h_{\text{surf}} &= v_{\text{surf}}(t) \cdot \Delta t \\ (\text{Distance} &= \text{Rate} \times \text{Time}) \end{aligned}$$

Thus, the volume of water that left the rocket, V_{surf}, is:

$$V_{\text{surf}} = h_{\text{surf}} \cdot A_{\text{surf}}(t)$$

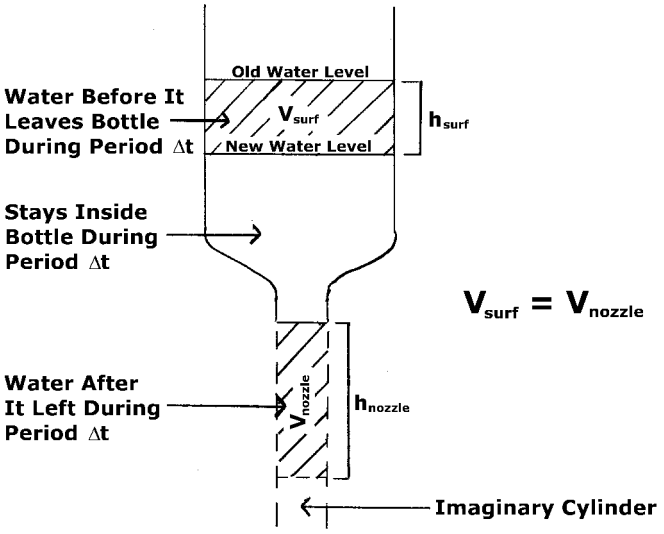


Figure 13.2: Proving there is an inverse relationship between the velocity and area of the moving water

Since this water had to go somewhere, it must have gone out of the nozzle, therefore there is now a volume of water, V_{nozzle}, that has come out of the nozzle. Assuming this water did not spray out, but stayed packed into a cylinder with the same diameter as the nozzle, this cylinder would have a height, h_{nozzle}, of:

$$h_{\text{nozzle}} = \frac{V_{\text{nozzle}}}{A_{\text{nozzle}}}$$

Since h_{nozzle} meters of water have come out in Δt seconds, working backwards from Distance = Rate $\times$ Time gives us:

$$v_{\text{nozzle}}(t) = \frac{h_{\text{nozzle}}}{\Delta t}$$

Since we must have the same amount of water at the beginning of the period Δt as we have at the end,

$$V_{\text{surf}} = V_{\text{nozzle}}$$

Substitution yields:

$$\begin{aligned} h_{\text{surf}} \cdot A_{\text{surf}}(t) &= h_{\text{nozzle}} \cdot A_{\text{nozzle}} \\ v_{\text{surf}}(t) \cdot \Delta t \cdot A_{\text{surf}}(t) &= v_{\text{nozzle}}(t) \cdot \Delta t \cdot A_{\text{nozzle}} \end{aligned}$$

Cancelling out Δt from each side yields:

$$v_{\text{surf}}(t) \cdot A_{\text{surf}}(t) = v_{\text{nozzle}}(t) \cdot A_{\text{nozzle}}$$

Therefore, we have an inverse relationship between the velocity and area of the moving water.

$v_{\text{nozzle}}(t)$ is the function which we are looking for. We will solve the equation in terms of $v_{\text{surf}}(t)$ so we can substitute later and get rid of the $v_{\text{surf}}(t)$ term:

$$v_{\text{surf}}(t) = \frac{v_{\text{nozzle}}(t) \cdot A_{\text{nozzle}}}{A_{\text{surf}}(t)}$$

Now, we are ready to calculate the velocity of the water leaving the rocket. We calculate this using Bernoulli's Law, which says that at any point along the flow of water,

$$p + d \cdot g \cdot h + \frac{1}{2} \cdot d \cdot v^2$$

equals a constant. p represents pressure, d represents water density, h represents height, and v represents the velocity of water. The first term accounts for the air pressure pushing against the water; the second accounts for the increased water pressure at the bottom due to gravity; and the third term accounts for the velocity of the moving water.

Using Bernoulli's Law for the surface of the water gives us:

$$[P_{\text{air}}(t) - P_{\text{atm}}] + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t) + \frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{surf}}(t)]^2 = \text{const}$$

First, notice the first term subtracts the atmospheric pressure from the air pressure. This is because the force of the atmospheric

pressure cancels out part of the force of the air pressure. For instance, if the air inside was at a pressure of 15 PSI and the air outside was also at 15 PSI, no propulsion would result.

Second, notice that the g, which represented the acceleration of gravity, has been replaced by $[a_{\text{grav}} - a(t)]$. This is because the rocket is accelerating, so we must account for the added acceleration, $a(t)$. $a(t)$ is subtracted to make this value negative, because of the "equal and opposite reaction" law—since the rocket accelerates upward, this creates a force which pushes the water downward.

Using Bernoulli's Law for the water in the nozzle gives us:

$$\frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{nozzle}}(t)]^2 = \text{const}$$

Notice that the first term disappears because there is no pressure acting on the nozzle (We took care of the atmospheric pressure when we subtracted it in the previous equation.). The second term disappears, because height is relative to the bottom, therefore the height for this equation is zero.

Since the constants must be equal, we can set these two equations equal to each other:

$$[P_{\text{air}}(t) - P_{\text{atm}}] + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t) + \\ + \frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{surf}}(t)]^2 = \frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{nozzle}}(t)]^2$$

Rearranging yields:

$$\frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{nozzle}}(t)]^2 - \frac{1}{2} \cdot D_{\text{water}} \cdot [v_{\text{surf}}(t)]^2 = \\ = P_{\text{air}}(t) - P_{\text{atm}} + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t)$$

$$\left(\frac{D_{\text{water}}}{2}\right) \left([v_{\text{nozzle}}(t)]^2 - [v_{\text{surf}}(t)]^2\right) = \\ = P_{\text{air}}(t) - P_{\text{atm}} + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t)$$

Substituting for v_{surf} gives us:

$$\left(\frac{D_{\text{water}}}{2}\right)\left([v_{\text{nozzle}}(t)]^2 - \frac{[A_{\text{nozzle}}(t)]^2 \cdot [V_{\text{nozzle}}(t)]^2}{[A_{\text{surf}}(t)]^2}\right) = \\ = P_{\text{air}}(t) - P_{\text{atm}} + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t)$$

Factoring out $[v_{\text{nozzle}}(t)]^2$:

$$[v_{\text{nozzle}}(t)]^2 \left(\frac{D_{\text{water}}}{2}\right)\left(1 - \left(\frac{A_{\text{nozzle}}}{A_{\text{surf}}}\right)^2\right) = \\ = P_{\text{air}}(t) - P_{\text{atm}} + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t)$$

Solving for $v_{\text{nozzle}}(t)$:

$$v_{\text{nozzle}}(t) = \sqrt{\frac{2\left[P_{\text{air}}(t) - P_{\text{atm}} + D_{\text{water}} \cdot [a_{\text{grav}} - a(t)] \cdot h_{\text{water}}(t)\right]}{D_{\text{water}} \cdot \left(1 - \left(\frac{A_{\text{nozzle}}}{A_{\text{surf}}}\right)^2\right)}}$$

Unfortunately, we're not done yet. We have only calculated the *velocity* of the water being expelled through the nozzle. We have not yet calculated the volume during the time period Δt, or the resulting force from expelling the water.

Calculating volume is easy. (Anything is easy after calculating the velocity!) We simply assume the water fits into a cylinder the size of the nozzle. Using Distance = Rate × Time, we get that the height of water, $h_{\text{expelled}}(t)$, expelled during Δt is:

$$H_{\text{expelled}}(t) = v_{\text{nozzle}}(t) \cdot \Delta t$$

Once we have the height of the cylinder, we calculate volume by multiplying the height by the surface area of the base:

$$V_{\text{expelled}}(t) = h_{\text{expelled}}(t) \cdot A_{\text{nozzle}}$$

Next, we convert volume of water into mass:

$$m_{\text{expelled}}(t) = V_{\text{expelled}}(t) \cdot D_{\text{water}}$$

Finally, we calculate the resulting propulsive force ($F_{\text{prop}}(t)$) created by expelling $m_{\text{expelled}}(t)$ kilograms of water at a rate of $v_{\text{nozzle}}(t)$ meters per second:

$$F_{\text{prop}}(t) = m_{\text{expelled}}(t) \cdot v_{\text{nozzle}}(t) \cdot \Delta t$$

13.6.5 Air Pulse

In addition to propulsion resulting from the expulsion of water, there is also another type of propulsion that the simulator does not consider: the release of the remaining air pressure after the water is gone. The "air pulse," as it is called, adds a small amount of thrust to any rocket launch—a rocket with no water will even go 10 to 15 feet in the air. An instantaneous acceleration could be added to the thrust for the time period, Δt, that this air pulse occurs. Another possibility to explore is the derivation of an actual formula to calculate the thrust resulting from the air pulse. Although we will not go into it here, more information on the air pulse is available on the Internet.

13.6.6 Parachute Drag

Parachute drag is calculated in the same manner as rocket drag, except it is typically in the opposite direction:

$$F_{\text{par}}(t) = \pm\frac{C_{pd} \cdot D_{\text{atm}} \cdot A_{\text{parD}}(t) \cdot [v(t) + v_{\text{updraft}}]^2}{2}$$

Like rocket drag, you must look at $v(t)+v_{\text{updraft}}$ to determine whether this is a positive or negative force.

13.7 Conclusion

Simulators are a great tool for developing rockets, because they allow you to test modifications in seconds, without spending the days required to do actual testing. The simulator covers some of the most important forces, but it does not cover every one. There are still many more factors that could be taken into consideration by a simulator, such as wind, air pulse, fin drag, stability, and bottle shape.

Appendix A

Water Markings

Since simulators can tell us the optimized water level for a particular rocket, we need a way to accurately measure the water in the bottle. The diagram below shows the standard water markings used on the pressurized bottle:

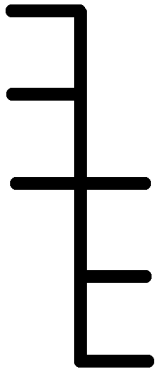


Figure A.1: Standard Water Markings

Notice that the markings have diagonal symmetry—when the bottle is turned upside down, the markings stay the same. This is important, because sometimes water is measured when the bottle is right-side-up (while putting the rocket on the launcher); other

times it is measured upside-down (while filling with water). This allows you to use the same water markings, no matter what type of launch set-up is used.

Since the markings are symmetrical, only one set is used at a time. The side on the right (which is always at the bottom) is the side that you will use. The lowest line represents the 30% water level for the bottle. Above it is the 40% water level. The top line (the longest one) is the 50% water level. **All water levels are measured from the *true volume* of the bottle, not what the bottle is marked as on the shelf!**

The following chart lists water markings for typical bottles. All measurements are in centimeters, and are measured from the bottom ring of the mid-section of the bottle.

Bottle Type	Volume	30%	40%	50%	60%	70%
1-Liter Poland Springs	1.10 L	2.5	4.0	5.5	7.0	8.5
2-Liter Coca-Cola	2.19 L	3.0	5.0	7.0	9.0	11.0

Appendix B

Stability Markings

Just as we can mark water levels on our rocket, we can also mark the stability. Stability markings are helpful on a rocket, because they allow you to change parachutes or other mass inside, without having to do the math or using a computer simulator to recalculate the stability. Here's a typical marking system:

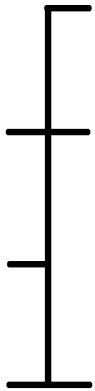


Figure B.1: Typical Stability Markings

The bottom line indicates the center of pressure of the rocket. The lines above it mark the center of gravity locations for 0.5, 1.0, and 1.5 calibers of stability. Remember, the distance between the center of pressure and center of gravity of a rocket with 1.0 caliber of stability is equal to the diameter of the rocket body.

With stability markings, testing your rocket for stability is simple. Pack your parachutes and any other parts of the rocket as if they were ready to fly. Then, try to balance the rocket body on the side of your finger. The point at which the rocket balances is the center of gravity. Use the stability markings to determine your rocket's stability.

Appendix C

Rocket Material Weights

In chapter 5, we looked at how to calculate a rocket's stability by using the plans, without actually building the rocket. To do this, you must first know the weight of the materials you are going to use, so you can accurately estimate the rocket's center of gravity. The values on the following pages contain weights of some common materials.

C.1 Bottles

The following table lists the mass of some 1 and 2 liter bottles. These values should be used for estimating the mass of the pressurized bottle of the rocket:

Volume	Brand	Mass
1 L	Poland Springs	37.8 g
2 L	Coca-Cola	48.6 g
2 L	Publix	50.2 g
2 L	Sam's Choice	51.1 g

For other parts of the rocket, which are made from pieces of plastic bottles, but not necessarily the whole value, we must look at the weight of each particular section of the bottle. For strength reasons, the plastic of the bottle varies in thickness. Typically, the neck and the base have the thickest plastic, while the flat, middle section is made of thinner plastic.

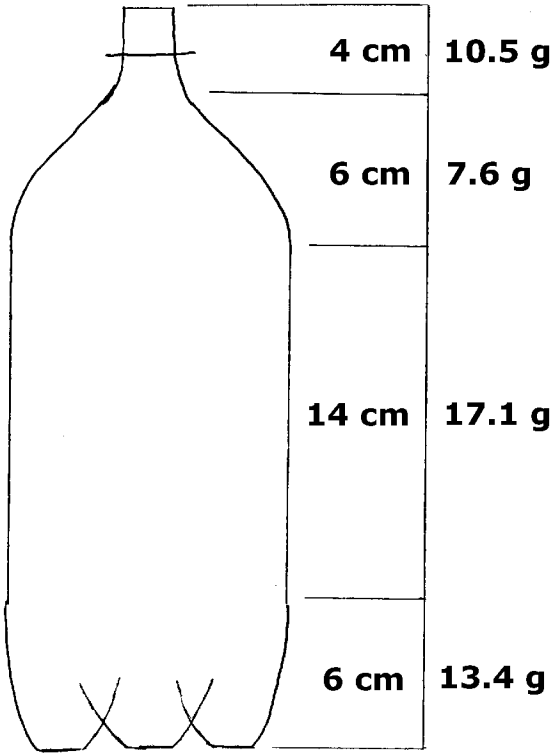


Figure C.1: Weight breakdown of 2 liter Coca-Cola bottle. (Total weight: 48.6 g)

If you are using the flat, mid-section from a bottle as part of your rocket, you can estimate the weight of it by using the following values:

Volume	Brand	Mass by Surface Area	Mass of Ring
1 L	Poland Springs	460 g/m^2	1.2 g/cm
2 L	Coca-Cola	350 g/m^2	1.2 g/cm

You can either use the values in the third or fourth columns, depending on how you measure your piece. If you know the surface area of your piece, convert the value to square meters, and multiply by the value in the third column. If you are cutting

a ring from the mid-section of a bottle, simply take the height, in cm, and multiply by the value in the fourth column.

C.2 Balsa Wood

Balsa wood varies in weight, so to get an accurate value, you must weigh the wood before you use it. The following chart lists common ranges of the weight of balsa wood:

Thickness	Mass
1/32"	50 – 150 g/m^2
1/16"	150 – 300 g/m^2
3/32"	300 – 600 g/m^2

C.3 Tape

Always use a light tape such as packaging tape when attaching rocket parts. Other tapes may be stronger, but are not necessary, and add excess weight to the rocket.

Tape	Mass by Surface Area	Mass by Length (2" Width)
Packaging Tape	60 g/m^2	3 g/m
Duct Tape	200 g/m^2	10 g/m
Aluminum Tape	300 g/m^2	15 g/m

C.4 String

Some type of string is needed for parachute shroud lines. Look for shroud lines that are light, but also very strong, as you can see in the chart below. Dacron weighs only slightly more than regular cotton string, but it is much stronger.

String	Strength	Mass
Cotton	5 lbs.	0.16 g/m
Dacron	30 lbs.	0.18 g/m

C.5 Other Materials

Here are some typical values for other materials that you may use while building your rocket:

Material	Mass
Cardboard	500 – 800 g/m^2
Dry Cleaning Bags	15 – 25 g/m^2

Appendix D

Parachute Materials Chart

This chart lists approximate thickness and density values for common parachute materials. The formulas for calculating a parachute's size and mass using these values were shown in the chapter *Elliptical Parachute Algorithms*.

Material	Thickness (cm)	Density (g/cm^3)
Plastic (Small Dry Cleaning Bag)	0.0021	0.730
Plastic (Large Dry Cleaning Bag)	0.0031	0.730
Tyvek (Priority Mail Envelope)	0.0188	0.342

Appendix E

Further Reading

The following Internet sites are filled with great information on water rocketry:

Baals Wind Tunnel
http://ldaps.ivv.nasa.gov/Curriculum/tunnel.html
A simple wind tunnel that can be built for under $200.

Clifford Heath's Water Rockets Page
http://www.osa.com.au/~cjh/rockets/
A simple water rocket simulator, plus lots of great water rocket links.

Dave Johnson's Water Rocket Annex
http://www.geocities.com/CapeCanaveral/Lab/5403/
Originator of the Airspeed Flap.

Paul Grosse's Water Rocket Index
http://ourworld.compuserve.com/homepages/pagrosse/h2oRocketIndex.htm
A large site containing various information on water rockets.

VCP CP/CG Stability Calculator
http://www.impulseaero.com/Software/VCP/index.html
The best program for calculating stability using the Barrowman Equations.

Water Rocket Equations by Den TAP
http://www.fortunecity.com/tattooine/cluster/145/rocket/theory/contents.htm
A great site, containing many of the equations mentioned in the *Simulators* chapter.

.... Composite Rocket Fuels ....

1.) Introduction

Composite propellants are solid rocket fuels that are composed of separate fuels and oxidizers mixed together in one homogenous mass. This propellant is then either molded into a grain to be inserted in an engine or cast in an engine casing and left to harden. The fuels and oxidizers taken separately are generally unreactive. Composite propellants are used in a number of engines. There are engines that use water for fuel and an oxidizer, air for an oxidizer like a ramjet, and a liquid/solid engine that can be throttled. The rocket motors discussed here a best built by the amateur with propellant weights below 2 lbs. and preferably under 1 lb. This is still powerful enough to shoot a sizable rocket to well over 4 miles altitude.
Before I get into propellant mixtures a few terms to learn are:

Specific Impulse - Defined as the impulse (force * time) delivered by burning a unit weight of propellant in a rocket engine.

Volume Specific Impulse - The product of specific impulse and density. This is expressed in pound-seconds per cubic inch. If the propellant's weight is kept constant, a propellant with a lower Isp but a higher density may outperform one with a greater Isp but a lower density.

Specific Force - This is a measurement of the ability for a gas to perform work. Specific force (F) is expressed in foot-pound per pound.

3.) OXIDIZERS

Composite propellants contain both an oxidizer and a fuel. The oxidizer may be a monopropellant and as such contributes power to the propellant mix. The ideal oxidizer should decompose into totally gaseous exhaust.

Oxidizers used in composite propellants : Potassium perchlorate ($KClO_4$). Potassium pechlorate was one of the first used oxidizers. One of it's draw-backs is the product of decomposition (potasium chloride) is not a gas at regular temperatures and does not contribute as a working gas. The KCl appears as a dense smoke in the rockets exhaust. Burning rates of propellants made with $KClO_4$ are usually high at 0.8 - 0.9 in/sec at 1000 PSI. Densities of fuels made with $KClO_4$ also tend to high at 1.8 - 2.0 gm/cc. Specific

impulses are usually below 200 lb-sec/lb. Potassium perchlorate is hardly ever used im modern propellants.
Ammonium Perchlorate NH_4ClO_4. This is the oxidizer of choice when possible. The products of diassociation of NH_4ClO_4 are 100% gas. The specific impulse of propellants using this oxidizer reaches 250 lb-sec/lb. Depending on the percentage of NH_4ClO_4 the burning rate may reach or exceed 0.5 in/sec. The products of exhaust are N_2, CO, CO_2, H_2, H_2O, and HCl. The HCl may pose some problem if the engine is used in high humidity as the HCl vapor may form visible hydrochloric acid fumes.
Ammonium Nitrate NH_4NO_3. This oxidizer is useful as it is usually available in bulk weight. The products of disassociation of NH_4NO_3 are 100% gas. However the temperatures produced by the propellant are low. For this reason,the specific impulse of NH_4NO_3 propellants are usually no greater than 180 lb-sec /lb and low percentage propellants have an Isp of 75 lb-sec/lb. The products of exhaust of NH_4NO_3 propellants are N_2, CO, CO_2, H_2, H_2O. These gases cause no special problems. The burning rate of NH_4NO_3 Propellants are low, ranging from 0.05 in/sec to 0.27 in/sec. The higher burning rates are possible if catalysts are used in the propellant. Prussian blue, chromium compounds (ammonium dichromate), or cobalt compounds are catalysts that are used. Ammonium nitrate is hygroscopic and undergoes a phase change if the temperature goes above 90 deg./F. Because of this phase change, some grains may crack if the temperature cycles about this temperature. The burning temperature of NH_4NO_3 propellants are lower than any other propellants especially at low percentages of oxidizer.
Lithium Perchorate $LiClO_4$. Some work has been done using lithium perchlorate as an oxidizer. The lithium chloride formed in the exhaust is a gas at high temperatures. Lithium salts are hygroscopic and must be protected from high humidity. Burning rates of $LiClO_4$ propellants are similar to $KClO_4$ mixtures.

4.) FUELS

Fuels Used in Composite Propellants : Since most rubbers and polymers are not available to the general public, some adjustments have to be made. A good source of plastics is an auto supply store. There you can find epoxy resin which can be used as a fuel. You will also find fiberglass resin. This is a liquid made from polystyrene and polyester resin. It is catalyzed with a few drops of hardener. PVC plastic can be dissolved in tetrahydofuran to make a thick paste. This can be mixed with an oxidizer and allowed to dry for an extended time to form a propellant grain. Asphalt was used in some JATO units about 30 years ago but it was found lacking when used at high temperatures. Some fuels used in commercial engines are polyurethane rubber, polysulfide rubber, and butadiene-acrylic acid. Non ferrous metals are added to propellants to increase the temperature of combustion and consequently the Isp. The metals most used are aluminum, magnesium, and copper. The metals are usually added in amounts of 5% - 25%. In engines designed to breath water as an oxidizer, metal amounts to about 50% to 80% of the weight of the propellant. The

other components are usually ammonium perchlorate and a polymer.

Propellant Grain Geometry : If the grain is ignited from end on, like a candle burns, the thrust will be steady or neutral. If the grain has a hole in it extending end to end and the combustion takes place from the inside out then the thrust will rise to a peak or be progressive. This is because the surface area of the grain becomes greater as it burns whereas in a neutral grain the surface area remains the same. A cruciform shaped grain produces a large amount of thrust first then tapers off because the surface area becomes smaller. If the grain is tubular and the combustion takes place from both the inside out and the outside in, then the thrust will be neutral but fast burning.
Wherever you wish the grain not to burn, it must be coated with a retardent. Epoxy works well as a retardent as does Elmers white glue. At least two coats of retardent should be used. An epoxy retardent can be used to retain a grain in a rocket engine. When tubular grains are used, the igniter is usually put towards the nose of the rocket and fires backwards towards the nozzle. This insures the grain is ignited completely.
Inspect the propellant grain for any cracks or imperfections. A crack can cause the surface area of the propellant to increase astronomically. This can cause an explosion because of the increased pressure.

5.) PROPELLANT MIXTURES

The ratios of oxidizers and fuels depends on the type of engine desired. The amount of oxidizer can be as high as 90% as in some ammonium nitrate mixes to as little as 20% ammonium perchlorate as in some water breathing engines.

A fast burning mixture: Potassium Perchlorate 20%
Isp=200 Ammonium Perchlorate 55%
Epoxy Resin/Hardener 17%
Powdered Aluminum 8%
This is very fast burning but the exhaust makes a fairly heavy smoke.

A slow burning propellant. Great for sustainer engines.
Isp=165 Ammonium Nitrate 70%
Ammonium Perchlorate 10%
Polyester Resin 18%
Powdered Charcoal 2%
Not very powerful but useful. The charcoal helps keep the combustion steady.

A very powerful mixture: Ammonium Perchlorate 75%
Isp=250 Powdered Aluminum 10%
PVC in THF 15%
All the ingredients should be dampened with THF (tetrahydrofuran) before

mixing. Do this in an area with very good ventilation and wear rubber gloves to keep from contacting the THF with bare skin. This mixture is best used in a perforated grain to help the solvent evaporate.

An ammonium nitrate based propellant: Ammonium Nitrate 70%
Isp=160 Powdered Aluminum 5%
Polyester Resin 18%
Ammonium Bichromate 5%
Powdered Charcoal 2%
A good mix when perchlorates are not available.

Do not under any circumstances use chlorates for rocket propellants. You will not make a rocket, just a pipe bomb with fins.

6.) COMPOUNDING PROPELLANTS

One thing to keep in mind when making a propellant, the volume of fuel/binder to volume of oxidizer and additives must not be too low. If it is then the mixture will be too dry to mix well. It will also hurt the strength of the grain. You may have to cut down on the amount of oxidizer depending on the fuel you are using.
For rockets weighing 1 pound and less the easiest way to make the propellant is to obtain a suitable container for mixing and put in the bottom of it the correct amount of fuel/binder. The other ingredients are added one at a time to the fuel and mixed in. One thing that really determines the success of a propellant is the particle size of the oxidizer. It should be as finely powdered as possible. Continue mixing the propellant until it is a homogeneous mixture. Now pour it or stuff it into the engine casing taking care to eliminate all air bubbles. Any mandrels needed to form the grain to shape shpould already be lubricated for release and in place. After waiting a suitable time for the binder to harden, remove the mandrels and place the engine in a warm place to finish curing. Inspect the grain for any cracks or imperfections.
Some large propellant grains are constructed by cementing smaller grains together. Disks of propellant can be glued and stacked to form a long grain. The disks can be drilled with a number of holes to make a progressive or regressive burning grain. The holes are lined up when the disks are stacked. If you construct a press with a number of guide rods to match the drilled holes, so much the better. The cement can be a very thin layer of the polymer used to make the grain. If you are using a PVC based grain, then dampen both mating surfaces with THF and press them together for a minute before adding the next disk.
You can also load a cardboard casing with the propellant. After the propellant is cured, this cartridge is loaded into the engine.
When drilling these propellants or using any power tool for shaping them, use

the lowest speed while checking to make sure no heat is building up on the cutting surface. If care is used, machining propellants is safe.

7.) ENGINE CONSTRUCTION

The typical engine is designed to operate at 1000 psi. The casing of the engine should be able to withstand at least 3000 psi as a safety factor. A low carbon seamless steel tube with 1/16" walls can withstand that sort of pressure. If the tubing has a welded seam, test fire a few engines to see if the tubes can take the pressure. One drawback to using steel as an engine casing is if the engine explodes you have some very lethal shrapnel flying around. If you use a high strength/high heat plastic you can eliminate some of this danger. Epoxy can be used to wet down a mat of fiberglass then the fiberglass is rolled around a large dowel to form a casing. The dowel has to be coated with a lubricant to keep the epoxy from gluing the casing and dowel together. Or you can obtain a heavy cardboard tube with the correct ID and coat it with epoxy then wrap epoxy/fiberglass around it. If the tubes are constructed properly they can take quite a bit of pressure before splitting apart.

An rocket engine is equipped with a nozzle to accelerate the exhaust out of the rocket at a high velocity. A nozzle has a convergent section that does this. A divergent section of nozzle is used to lower the exhaust pressure so the exhaust gases accelerate out of the engine at high speeds.

The nozzle of the engine can be machined out of metal or made of a fireproof ceramic. If the nozzle and the casing are metal, they can be brazed together before the engine is loaded. The nozzle can also be screwed into place by using 4 - 6 screws going through the side of the casing into the nozzle. Care must be used to see that the screws don't break through the inside of the nozzle. On smaller rockets, you may be able to get away with plaster of paris nozzles or for more powerful motors try pressing a mixture of 90% kaolin and 10% aluminum oxide into a nozzle shape in the casing. Dampen the mix with a little water before pressing. You can make a nozzle die by turning 2 pieces of hardwood into divergent/convergent sections. This die should be fitted with a dowel guide pin at the mating points to help keep the die straight.

A nozzle can be made from just a divervent section. This can be easily made by drilling the required hole in a section of nozzle. Then by drilling out the first hole with larger drills without completely breaking through, a diverging nozzle is formed. Smooth out the ID of the nozzle after drilling the holes. This type of nozzle is pretty good on smaller engines with a 1" ID or less. By using some ingenuity, you should have no problem in making a servicable nozzle. A rule of thumb to use for the ID of the nozzle is to use a hole that has an area (repeat-area,not diameter) 1/3 the area of the ID of the rocket engine casing.

Most propellants burn unsteadily at low pressures. Solid rocket engines are equipped with a blast plug that allows the pressure to build up in the engine before being blown out like a cork in a bottle. Sometimes the ignitor is

combined with the blast plug in a single unit. A stiff plastic disk makes for a good plug. It should have a thickness of about 1/16".
The engine is sealed with a plug in the fore section. Depending on the construction of the engine this plug may be made of wood, plastic, or metal. It is held in place with either screws or epoxy. This plug must make the casing gas tight. Remember most rockets develop 1000 PSI.
The ignitor is simply an electric match. It can be made with nichrome wire or a small light bulb. The match is used to ignite a small charge of black powder that in turn ignites the propellant. The ignitors leads should be shunted together to eliminate premature ignition. A fuse can be used instead of electric ignition. If you go this route, be sure of the burning time of the fuse and allow yourself enough time to retreat to safety after igniting the fuse. I cannot recommend using a fuse because you cannot stop a fuse from burning if someone walks into your launch area. With electric ignition, everything is under your control until the time of launching.

8.) Engine Design

It would be nice to be able to give you the complete info on designing rocket engines. However, the required math would be a file about 300K in length. Also this file is mainly about propellants. The other info is gravy.
The best I can offer is to check out your local library for design and engineering books. If you want to build a rocket to simply shoot off to stroke your pyro perversions, build a small engine containing no more than 4 oz. of fuel. Use a paper casing to keep the danger down and chances are very good that if your construction is sound you'll get the thrill of seeing your rocket go out of sight. If you plan to hoist a payload into suborbital projectory however, learn about thermodynamics, interior ballistics, and propellant chemistry.
I recommend trying to get the book Amateur Rocketry Handbook. This book is out of print but it was put together by the Fort Sill Artillery School and contains a lot of valuable info.

9.) Testing and Firing

You should construct a few engines exactly the same and test fire a number of them to find out what to expect when you finally do launch a rocket . The engines can be buried nozzle end up in the ground and fired. Time the burning of the engine to figure out the rate of combustion of the propellant. Inspect the casing to see how it stood up. If everything seems okay you can construct a static testing fixture to measure the thrust. Keep in mind that even a small engine can put out a few hundred pounds thrust for a split second. When you do launch a rocket, keep people away from the launch site and under cover. Check out the skies for airplanes or other traffic. Don't launch rockets under conditions of low visibility or heavy winds.

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I. Introduction

Improvised rocket motors provide a simple means for irregular forces to deliver military payloads to ranges beyond individual hand weapons without complicated launch means. Improvised rocket techniques can be exploited to increase the firepower and effectiveness of guerrilla-type forces. Having the great advantage of not requiring heavy launching equipment, such as conventional mortars and artillery pieces, rockets are aptly suited to the characteristics of operations and capabilities of irregular units whose weapons must be concealed between use and whose transport and logistics means are restricted to that common to the area of operations.

The advantages of an improvised rocket munition are:

A. Recoilless operation.

B. Simplified launching techniques and apparatus. (A mound of dirt may suffice in the simplest case.)

C. High degree of mobility. (Only the payload, motor and ignition device need to be carried.)

D. Munitions can be fabricated from materials available from the environment or the local economy.

E. Unskilled labor can be used for manufacturing operations.

F. The identity of the manufacturing effort can be easily concealed.

This report will investigate a system using and providing the following features:

A. Use of common materials for construction (pipe, pipe caps and nipples; saltpeter and sugar; wooden dowel, et cetera).

B. Recoilless, flashless performance.

C. Adaptability to a wide spectrum of payloads and ranges.

D. Suitable for a variety of ignition means including powder train, hot wire, blasting fuse or homemade fuse.

E. Capability of being fired remotely or with a minimum of 20 seconds delay for operator security.

F. Capability for instantaneous firing of multiple round salvos or single rounds (for harassment or ranging).

G. Establishment of a relatively "standard" rocket carrier design, determined from the materials available in the particular area. (This will simplify the ballistics and provide the forces with a predictable weapon.)

Section II, "Technical Discussion", describes the analysis and design approach to be used in providing the improvised hardware. It also outlines the problem areas and considerations in providing reasonably useful munitions in a surreptitious fabrication situation where quality control and manufacturing processes must be accomplished without tools other than common hand tools and "eye ball" instrumentation.

II. Technical Discussion

A. BACKGROUND

In the period 1947 to 1957, a large number of amateur rocket experimenters were engaged in the manufacture and testing of rudimentary rockets. By 1947, the information from the World War II rocket technology began to become documented and disseminated, catching the imagination and interest of many young experimenters. These persons, working alone or banding into groups, produced many hazardous, and even lethal, rocket-propelled missiles. Unfortunately, the hazardous nature of the propellants selected, such as match heads, shotgun shell powder, and home-brewed mixtures of volatile and inflammable materials, proved more dangerous in the basement or garage laboratory than on the firing range. The large number of injuries from the uncontrolled experimentation led to many local ordinances and laws prohibiting the sale of certain materials and also restricting the firing activities to areas where adequate supervision could be provided. This general awareness of the hazards of rocket experiments began about 1957, evidenced by the American Rocket Society adopting an official organizational position opposing amateur experimentation outside of qualified supervision. In spite of the restrictions, the experimenters still found common materials which could be adapted to produce rocket hardware.

During the decade of more or less widespread amateur experimentation in rocketry, many combinations of propellant formulations were made and tested. Ingenious experimenters devised ways of extracting nitrates from the cheap and readily available fertilizers having this compound. Mixing this source of oxygen with various fuels provided very adequate rocket propellants. One of the materials found to

be readily accessible was sugar. A sucrose-potassium nitrate formulation provides a specific impulse (as derived from ballistic bomb data) of about 130 - 140 seconds. In actual rocket motor performance on the order of 105 seconds is readily attainable. This compares with an I_s of 200 for M-7 propellant, currently in wide use in military rockets.

In preparing this book several pipe rockets were assembled and tested against wooden targets at short range, demonstrating the feasibility of the propellant and body structure.

This study proposes sucrose-potassium nitrate for the improvised rocket propellant. Both these materials can be obtained in most of the world, particularly in those areas where insurgency operations are most probable. These designs for an improvised rocket will concentrate on this propellant mixture as the "standard."

In providing an improvised munition of this type, this study will give attention to the following areas:

A. Propellant grain formulation and configuration.

B. Grain installation in rocket body for integrity in rough handling, storage life expectancy and reliability in handling.

C. Assessment of environmental effects such as operating temperature ranges for various possible geographical areas, humidity and fungus.

D. Safety.

E. Training.

F. Effects of variations in materials of construction on safety and performance.

G. Security Aspects

Means should be provided to conceal the true nature of the items being fabricated.

H. Launching preparation should be simple allowing rapid setup and firing.

I. Signature effects at the launch site should be minimum.

J. High reliability of operation should be obtained to avoid problems of disposal of duds.

Our effort will provide:

A. Specific hardware designs and sample prototype units of rocket motors of simple design constructed from common materials such as would be readily available to guerrilla-type forces.

B. Generalized design guidance for instruction of guerrilla personnel in the construction of improvised rockets, including safety precautions.

C. Descriptions of firing procedures, including rudimentary ballistics and fire control under probable conditions of use.

D. Investigation of reliable ignition methods. Also, means for ignition of the improvised rockets for firing individual rounds and salvo or ripple firings of multiple rounds.

E. Report of effects obtainable from the improvised rounds, including: range, payload, probable dispersions under standard and non-standard conditions and possible type payloads.

F. Prediction of degradation in performance from optimum due to fabrication variances, materials impurity, field handling, storage and environmental conditions.

B. DESIGN CONSIDERATIONS

This study's proposed design will be based upon rockets using materials obtained from normal agricultural, construction or commercial sources. Referring to the early work done by the amatuer groups in the practical application of rocket design theory to their hardware, their experience indicates that some experimental verifications and detailing is required before scale-up of their small diameter rockets (½ to ¾ inch water pipe bodies) to militarily useful diameters (minimum of 2 inches). These include:

A. Length to Diameter (L/D) Ratio

A certain maximum (L/D) ratio cannot be exceeded without generation of excessive chamber pressures, which can rupture the chamber wall.

B. Propellant "Watering"

A certain content of water is necessary for efficient performance. This has been referred to as an "aid for compaction" by some amateur groups, but the real mechanism affecting performance must be determined.

C. Port Diameter to Nozzle Diameter

The usual rule, that the port area must be two to three times the nozzle area does not seem to hold rigorously for the rather soft, erodible grain formed by KNO_3/sugar. This should be investigated.

D. Effective Burning Area To Throat Area (K_n)

Attempts have been made by the amateurs to correlate various working geometries by K_n. Attempts indicated that a probable mass-action or permeable burning effect makes this relationship not wholly straightforward. This will have to be definitized before motors larger than two inches can be designed.

Data is on hand from the firings of over a thousand rockets assembled and fired by a group of private experimenters comprising a rocket research association, now disbanded. This group, although using rudimentary materials for construction, maintained their records of fabrication and testing in a professional manner and in sufficient detail to reproduce their designs. The bulk of the (more than a thousand) units prepared by this group were rockets fashioned from standard ½ inch and ¾ inch pipe. It is believed that similar designs can be scaled upward to provide rockets of two inch diameter having a maximum range of 1,000 meters carrying a one pound payload, or correspondingly shorter ranges for greater sized payloads.

C. DESIGN CONFIGURATION AND PERFORMANCE

A ".62 standard" (.62" is the inner diameter of common ½ inch water pipe) motor has been fabricated and test units fired with piezo-electric gauges attached. Burning times are much shorter and thrust levels higher than performance of the propellant in amateur testing has indicated. However, the total impulse seems to agree quite well. On the basis of these tests, a set of curves was drawn to show payload delivery capabilities for the ".62 standard" and also a ".82" motor (¾ inch pipe). These curves are shown in Figure 1.*

A one pound payload, as an example, can be projected to 600 feet with a .62 motor and more than 1,500 feet with a .82 motor. Extrapolating to a two inch pipe motor gives a range of nearly 12,000 feet for a one pound payload.

A conceptual drawing of an improvised rocket motor embodying the concepts outlined in this proposal is shown in Figure 2.

Figure 3 shows the procedure for loading KNO_3/sucrose propellant. After compacting the grain with the hollow tamper, the mandrel (dowel) is removed to leave the perforated grain.

D. DEVELOPMENT PROGRAM

In providing an improvised rocket concept, this study proposes:

A. Examination of basic design models to establish definitive criteria involved in predictable scaling of motors to meet variable diameters and characteristics of possible body construction materials.

B. Performance of testing to validate and formalize the scaling laws.

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* *Although pipe sizes in a given area of employment may not be identical with standard U.S. pipe dimensions, performance should be comparable.*

Curves are computed from the equation given in Paragraph E with the total impulse obtained from actual rocket tests.

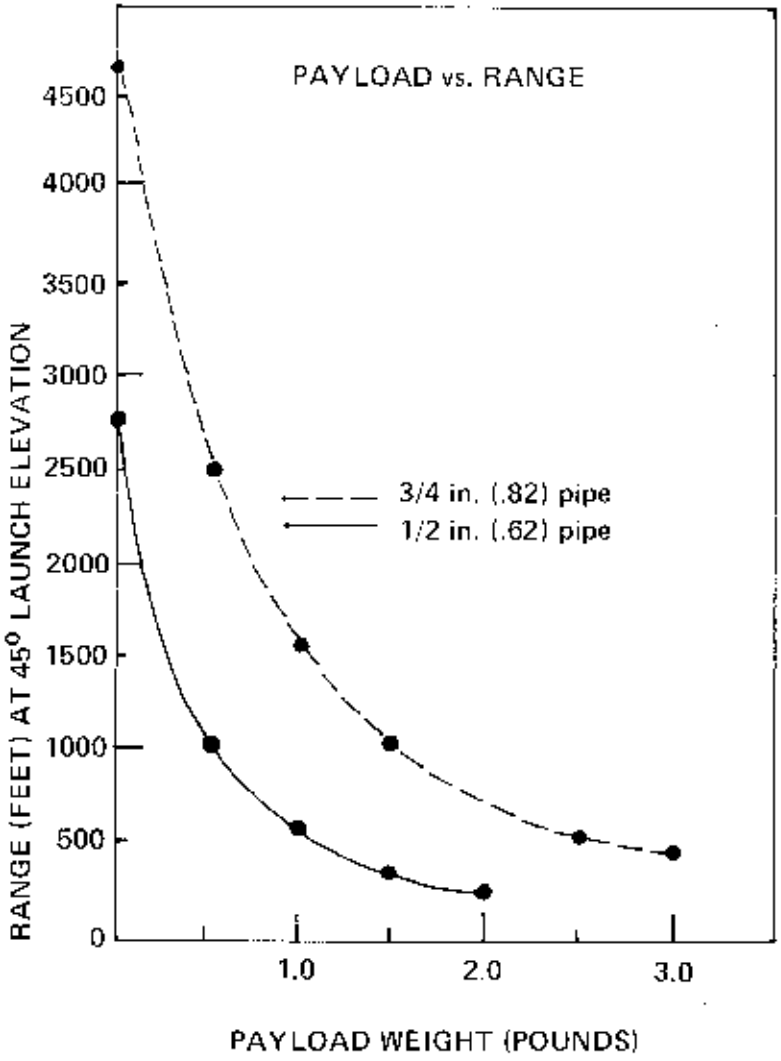
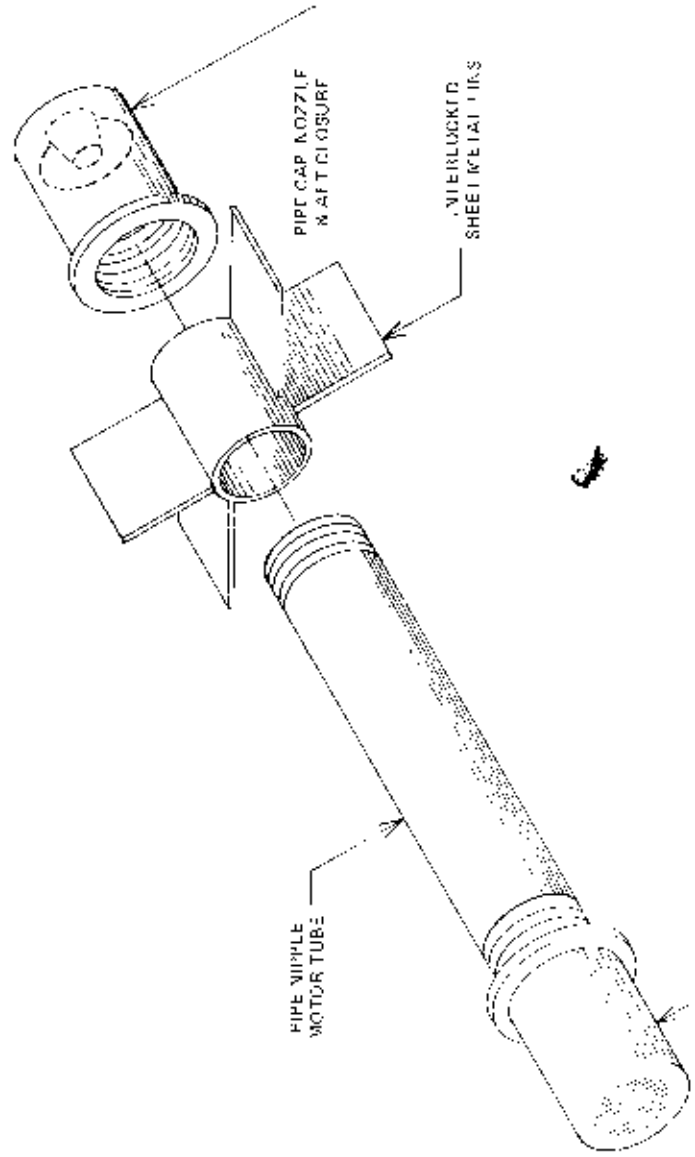


Figure 1



IMPROVISED ROCKET MOTOR
Figure 2

LOADING TECHNIQUE
For Improvised Rocket Motor

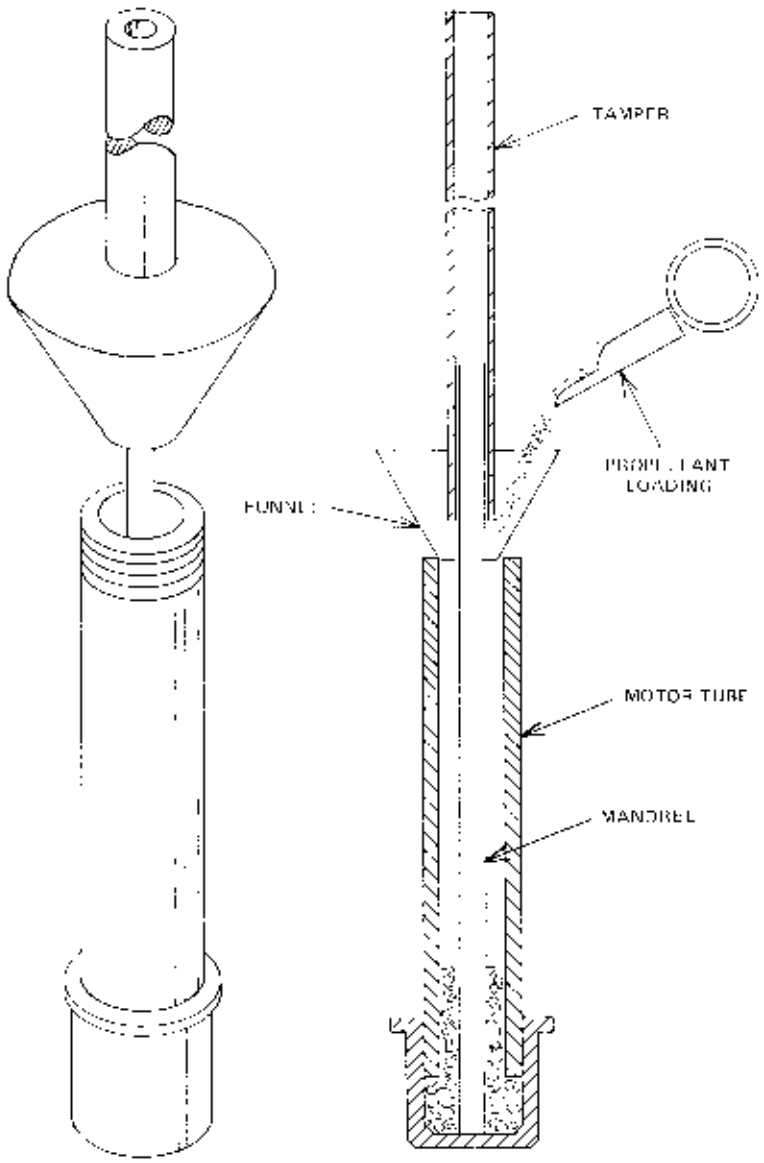


Figure 3

C. Design and development of a typical improvised rocket motor suitable for construction by unskilled personnel using commonly available materials and tools.

D. Fabrication of 65 each prototype pipe-bodied rockets (all loaded with KNO_3/sugar propellant), of the following pipe sizes:

1/2 inch
3/4 inch
1-1/2 inch
2 inch

E. Test firing of the above units, expending 25 of each type in static tests for characterization and 40 each in payload versus range tests, with 1/2 to 3 pound inert heads. Impact pattern data will also be collected for an indication of dispersion.

F. Preparation and submittal of a final report describing the designs, fabrication procedures for field accomplishment, firing and launching procedures, safety measures and the program activity accomplished during the program. A supplement will be prepared for the improvised weapons handbook for each size rocket motor tested and range tables provided.

In addition to the basic rocket carrier, it is proposed that a study be made of the employment of the rocket as a practical weapon, including possible payloads and the implications and interface considerations between the payloads and the rocket. The effort will include:

A. Study and design of ignition means for individual and multiple round firings, including delay provisions.

B. Payload interface investigations, including recommended payloads, methods of attachment, arming and activation, performance characteristics and modifications required to adapt rocket and payload.

E. PERFORMANCE OF POTASSIUM NITRATE/SUGAR PROPELLANT

A composition of 70% Potassium Nitrate Technical Grade, 100 80 mesh (Tyler) with 30% sucrose, commercial grade, crystalline, plus 3-5% water to aid in compaction for grain fabrication (internal burner only) has been tested in ballistic bombs, providing the following data:*

Assuming a molecular weight (MW) = 30

Ratio of specific heats (k) = 1.21

Temperature of combustion (T_c) = 2640°R

Gives a specific impulse (I_s) = 137 sec (500 psi → 15 psi)

In a particular motor, the following determinations were made:

Characteristic exhaust velocity (c*)	= 3080 fps
I_s	= 105 sec
With a thrust coefficient (C_F)	= 1.10
At a propellant density	= 0.05 lb/in^3
Burning rate (r_b)	= 0.28 in/sec (at 800 psi)
Lower limit, combustion chamber pressure (P_c)	– about 100 psi
Upper limit, P_c	– more than 7500 psi

* *Although commercial purity materials may not be available to field forces, standard materials are cited here for reference and later comparison with actual results obtained. The degradation of performance from the use of "field grade" purity compositions will be investigated. It is possible, however, that materials can be obtained in pure form, thereby achieving optimum performance.*

The performance of this propellant, then, is slightly superior to black powder. The specific impulse derived from motor data was used to compute the range versus payload graph of Figure 1 as follows:

$$\text{Range at } 45^\circ \text{ elevation} = \frac{1}{g}\left[\frac{I_T\, g}{w_m + w_p + \frac{w}{2}}\right]^2$$

Where:
- g = gravitational acceleration 32.2 ft/sec^2
- I_T = total impulse, lb-sec
  - = specific impulse x propellant weight
- w_m = weight of motor, lbs
- w_p = weight of payload, lbs
- w = weight of propellant, lbs

F. PAYLOADS AND MISSIONS FOR IMPROVISED ROCKETS

Once the basic propulsion unit is available, only the ingenuity of the guerrilla personnel limits the possible missions for the rockets. A number of payloads are immediately suggested, ranging throughout the spectrum of regular munitions. Possible missions are shown in Figure 4.

There are some types of payloads such as incendiary mixtures and biological materials which can be put together quickly by the guerrilla fighter, for example, the Molotov cocktail mixture.

It would be possible to assemble improvised "tomato can" munitions for use with the improvised rocket. High explosive charges, surrounded by available small hardware such as nails and bolts could be prepared for delivery with the improvised rocket.

IMPROVISED ROCKET MOTOR MISSIONS

OFFENSIVE OPERATIONS

- Antipersonnel
  - Grenade throwing (shrapnel, concussion, tear gas)
- Antivehicular
  - Shaped charge
- Antistructural
  - Shaped charge
- Antiaircraft
  - Ripple firings or simultaneous launch of rockets carrying aloft trailing wires
- Sabotage
  - Remote firing of pre-positioned and concealed units into a secured area
  - Projection of conductors over high tension lines or into transformer stations to short out service circuit

SUPPORT MISSIONS

- Line Throwing
  - Access across obstacles
  - Projection of telephone wires between two friendly positions
- Signaling
  - Projection of flares and smoke
  - Projection of message containers

Figure 4

It is assumed that the guerrilla forces will be armed to some degree with conventional weapons, particularly hand guns and grenades. The most effective payload for the improvised rocket is the grenade: the proposed primary mission is as a grenade thrower. Available in a variety of fillings, the grenade provides a reliable, self-contained unit easily affixed to the improvised rocket carrier by insertion in an open ended can fastened to the rocket head cap. The can would be of a size to allow pulling of the grenade safety pin while restraining the hand safety clip of the U.S. type grenades. Air drag during flight can be used to separate the grenade from the can, or the grenade can be arranged to separate (and arm) at ground impact. Other arming innovations can be devised for friction match (pull type) igniters of some foreign grenades.

The improvised rocket's great advantage is that it can be made in moderate numbers quickly with ordinary hand tools, or its parts can be pre-fabricated and stored as partially finished stock, presenting the appearance of some unsuspicious commercial product. When needed, the units can be loaded rapidly and assembled into the tactical configuration. Payloads can be affixed and even final assembly can be accomplished under cover or concealment at or near the launch site. Components can be brought into the assembly area by separate persons for security of the operation and personnel. A typical launch area setup showing a powder train ignition method is depicted in Figure 5. The circular launch configuration and the central origin for powder trains to each rocket allows ripple firings without one rocket exhaust extinguishing the powder train of adjacent rockets. The launch support shown in Figure 5 is a simple forked stick cut to a size to allow the 45^{0} launch angle. This is accomplished by providing the vertical height of the support to be 7/10th of the length of the rocket body to the point of support.

In addition to stick supports, mounds of dirt, convenient embankments, drain pipe or stove pipe, wooden troughs or a variety of other materials as available in the area can be used for rocket positioning and initial directional control.

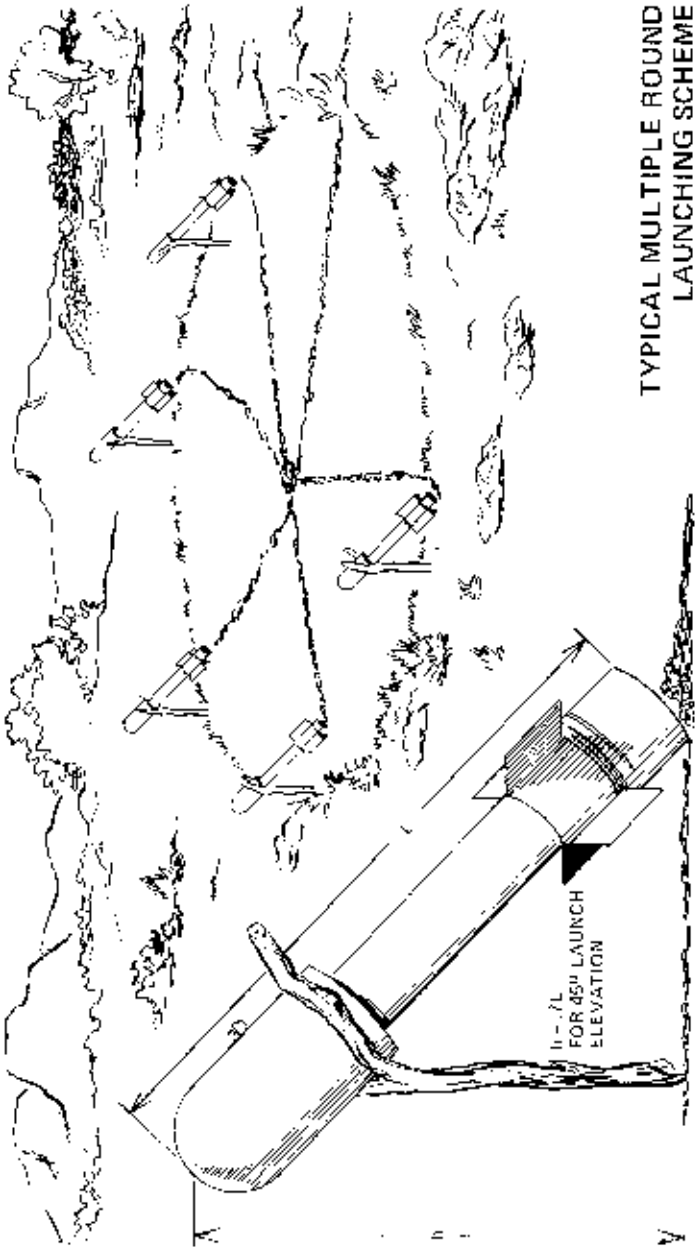


Figure 5

Figure 6 shows examples of ignition means which can be used for firings of individual or multiple rounds.

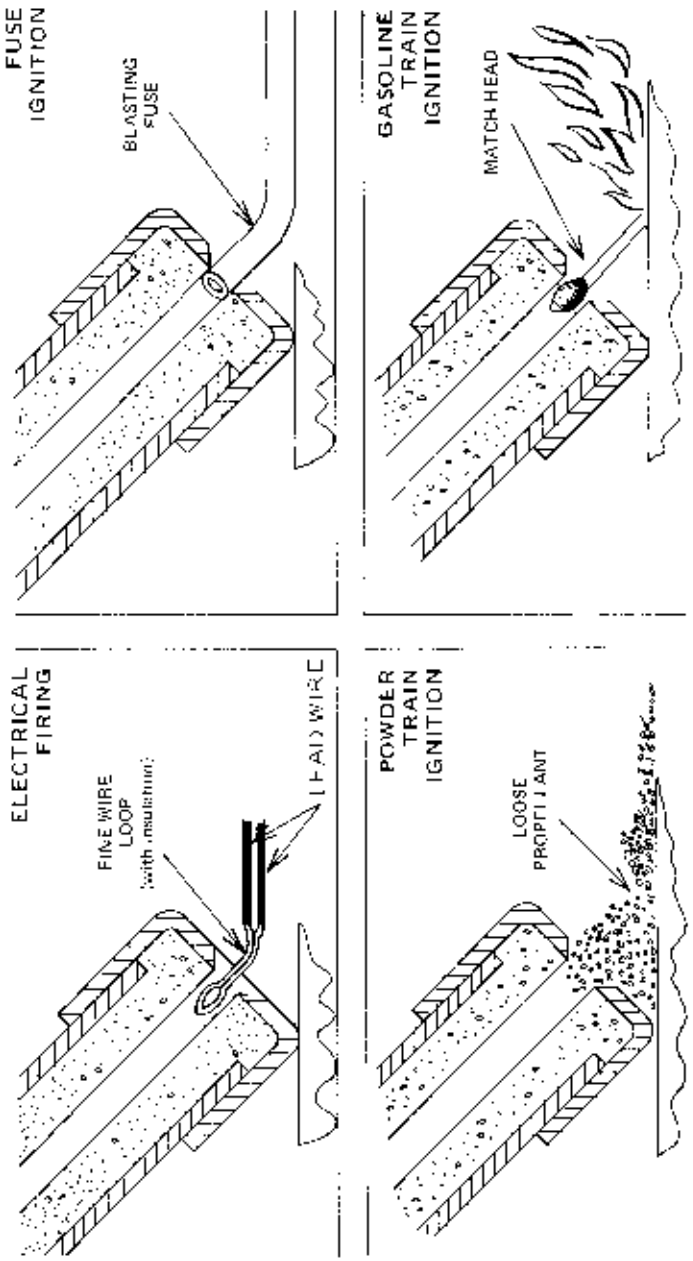
G. TACTICAL EMPLOYMENT

Although the improvised rockets are of relatively small size, they can be used for projecting relatively heavy payloads for short distances. For example, they might be used as anti-vehicular or even anti-tank weapons. In such use, the rocket would be pre-positioned with its warhead and ignited remotely. A typical emplacement might be in an embankment flanking a defile or road traveled by vehicles. A very large warhead could be projected on a relatively flat trajectory for a range of 10-50 meters.

The fabrication of shaped charge devices is readily accomplished in the field. For example, the bottom configuration of many wine bottles forms an excellently configured mold and liner for a shaped charge. It is also possible to improvise an impact initiator using sodium chlorate, sugar and sulphuric acid (car battery acid).

The possible use of the improvised rockets as antiaircraft weapons should not be discounted. Arranged in arrays under the approach or take-off patterns of airports, or pre-positioned in probable landing areas for aircraft or helicopters, the improvised rocket could prove a reasonably effective one time weapon. It would also be possible to use the rockets for air defense of an area by launching salvos against pre-selected points in the airspace over the guerrilla position, firing the rockets upon the approach and passage through the airspace by the target aircraft.

An interesting mission for individual rockets is in the throwing of lines. A large variety of uses is possible here. In acts of sabotage, conductive wires can be projected over high tension lines or into transformer stations to short out circuits of the electrical supply. Since critical electrical facilities are likely to be under close security guard or surveillance, an ability to reach the installation by rocket fired from a secure point outside the security area provides access which might otherwise be impossible for the saboteurs.



IGNITION METHODS
Figure 6

The same wire pulling technique can be used for friendly support purposes — to interconnect two positions with telephone cable or to place a lead line across an obstacle to draw across a heavier interconnection for further access across the obstacle.

The improvised rocket would be best employed with payloads and missions which exploit the basic features of the improvised device. These missions are:

A. Grenade throwing for anti-personnel and limited structural damage.

B. Line throwing for access into secured areas or in spanning obstacles.

The guerrilla force having a rocket capability will find missions for its employment to meet many needs arising in their environment. They will use both individual rockets to solve specific access problems and multiple round firings for their defensive and offensive operations. The improvised rocket will add a shock and surprise capability to insurgent operations. It will give the agents not only greater striking opportunity but better security and ability to escape after actions. Once used by the guerrilla force, rockets will expand the opposition's manpower required for the security of vital installations, making the counter-insurgency effort more burdensome and costly.

The improvised rocket will add a dimension to guerrilla operations impacting both the tactical and psychological areas of the insurgency situation. The rocket capability will strengthen the effectiveness and morale of the guerrilla force, while presenting the opposing authority with a new and unexpected problem. Increased suppressive effort over larger areas must be applied to counter the suddenly increased vulnerability of his installations, equipment and personnel. At a very low cost to the guerrilla in time and effort, his harassment value will be enhanced significantly through addition of the improvised rocket to his "arsenal".

APPENDIX

Table I, following, gives the results of more than 1,000 test firings of potassium nitrate/sucrose propelled rockets using a propellant formulation as described in Paragraph E, Section II, "Technical Discussion". Tests were conducted during the period 1947-50. Notation used on Table I follows the conventions outlined in the section following the Table: "Simple Expressions For Quick Look Estimations of Solid Propellant Rocket Motor Performance".

SUMMARY OF ROCKET MOTOR TESTS WITH KNO_3/SUCROSE PROPELLANT

GRAIN					K_n	$F_{Lbs.}$	C_F	Number of Nozzles	P_c Lbs./In.^{2}
TYPE	O.D.	I.D.	LENGTH	WEB					
Restricted End-Burn.	1.93	No Perforation	13	13	14	-	-	5	-
Circular Perforation	.622	.25	6	.136	191.3	35	1.10	1	1,300
Circular Perforation	.622	.25	6	.136	170.8	35	1.10	5	1,150
Circular Perforation	.622	.1885	6	.217	143.8	37.5	1.10	1	1,385
Circular Perforation	.622	.1885	6	.217	128.1	37.5	1.10	5	1,232
Circular Perforation	.93	.25	12	.340	123.0	-	-	1	-
Restricted End-Burn.	.824	No Perforation	4.7	4.7	19.6	4	-	1	135
Circular Perforation	.824	.40	10	.212	128.2	58	1.21	5	490
Circular Perforation	.824	.40	10	.212	110.0	42	1.21	1	314

SIMPLE EXPRESSIONS FOR QUICK-LOOK ESTIMATES OF SOLID PROPELLANT ROCKET MOTOR PERFORMANCE

Basic Equations

$$F = A_t P_c C_F = A_b \rho_s r_b = \frac{I_T}{t_b} = I_s \dot{w}$$

$$I_s = \frac{c^* C_F}{g} = \frac{I}{t_b \dot{w}} = \frac{F}{\dot{w}}$$

Typical Values For Solid Rocket Parameters

	Potassium Nitrate	Ammonium Nitrate Composite	Ammonium Perchlorate Composite	Aluminized Composite	Potassium Perchlorate	Double Base
1.25 can be used as a k value for all propellants						
r_b(in./sec) 1,000 psi	.25	.1	.20	.25	1.5	1.5
I_s 1,000 psi	130	150	200	235	180	220
500 psi		1,000 psi	1,500 psi	3,000 psi		
C_F	1.46	1.55	1.60	1.65	Note: Max C_F = 2.246	
k	5	7	10	18		

CLOSED BOMB DETERMINATION OF SPECIFIC IMPULSE:

Bomb Volume = V, cc

Propellant Weight – w, gm

Maximum Pressure – P, lb/in^2

Impetus = F_{imp} ft-lb/lb

$$F_{imp} = k_1 \frac{P}{w/V}$$

k_1 – 2.307 (covolume and dimensionless unit conversion factor)

$$c^* = k_2 (F_{imp})^{1/2}$$

k_2 – 7.72 (unit conversion factor)

$$I_s = \frac{c^* C_F}{g} - K_3 C_F (F_{imp})^{1/2}$$

k_3 – 0.240 (dimensionless factor)

$$I_s = k_4 (F_{imp})^{1/2}$$

1,000 psi

k_4 – 0.379 (unit conversion factor)

NOTE: Constants k_1, k_2, k_3 and k_4 above are empirically derived factors which give approximations to the quantities expressed for quick look evaluations of the proposed solid propellant rockets as derived from amateur group experiments.

BIC FARRELL

BACKYARD ROCKETRY

Converting Model Rockets into Explosive Missiles

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INTRODUCTION

This book contains extracts from the official constructor's handbook of the Dangerous Rocket Club, a completely fictitious organization that I made up in order to start this introduction.

It will show you how to build short- and medium-range surface-to-surface and surface-to-air missiles using off-the-shelf components and no tools (well, hardly any). Also included are designs for shoulder-launched rockets and warheads.

At last, those hard-to-reach targets are yours for the taking. City Hall, the local IRS offices, that damned polluting nuclear facility, whatever. You might even want to take a few to the next paintball game.

Using the techniques shown, it is also possible to make fully operational replicas of those neat multiple rocket launchers you've seen in Gulf War footage on TV. Using these (and assuming a suitable Iraqi target), you and your friends can re-enact the operation to your hearts' content. If you don't have a nearby Iraqi/Muslim community or can't locate a handy mosque, don't fret; you can find the addresses of relevant embassies in the Yellow Pages. These make great secondary targets.

The devices described here are based on flying model rocket components of the type available from hobby shops. Complete kits—which include engines, electrical igniters, launch pads, etc.—can be purchased over the counter.

A "Model Rocket Safety Code" exists, which, if followed,

ensures clean, safe fun for kids of all ages. A copy of the code will be supplied with most store-bought flying rocket kits or suppliers' catalogs. The Dangerous Rocket Club's version of this code appears in **Appendix III**. If followed, you will probably go to prison.

The engines and rocket kits themselves are supplied in configurations that ensure that altitude/distance and payload capabilities are kept within safe parameters. By modifying and adapting engines and rockets, however, it is possible to create missiles that have a far more "useful" range and capacity!

Disregarding established Model Rocket Safety Code rules and experimenting with model rocket engines can be dangerous. Installing explosive components into such rockets is definitely dangerous and also illegal. Only persons with a sound and proven knowledge of explosives handling and use should ever experiment with such substances, and even then, industry standard guidelines must be followed.

In any event, neither the author nor the publisher advocate or seek to encourage any breaches of the Model Rocket Safety Code or explosives laws and offer this book for information purposes only.

CHAPTER 1

OVERVIEW

Flying model rockets are constructed from lightweight materials such as cardboard tubes, plastic, and balsa wood. Despite this, the completed devices are surprisingly resilient.

Kits are available in a variety of styles, ranging from simple, relatively inexpensive firework-size units to expensive scale replicas. Once the basic principles are understood, all component parts can be improvised easily, and the instructions provided with one kit can be used to make more rockets from components obtained elsewhere.

Assembly can take minutes or hours, depending on the level of complexity of the model. The tools required are a hobby knife, sandpaper, and some wood glue. Balsa wood sealer may be used prior to painting for a smoother and slightly more resilient finish. Enamel spray paint can be used for finishing, and this, too, helps "harden" the rocket.

The majority of commercial rocket kits include a parachute or streamer assembly that deploys at the end of the propellant burn period (more on this later) to facilitate safe recovery of the rocket. In the context of this book, parachutes or streamers would probably only be used as part of air-burst projects and during testing.

As supplied by the manufacturers, the rocket engines are completely safe. They are so safe, in fact, that the U.S. Department of Transportation (DOT) classifies them as "Toy Propellant Devices," and they may thus be shipped through

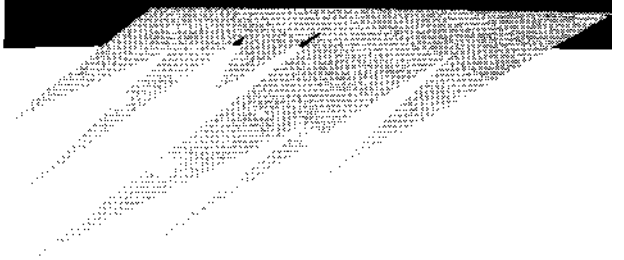
the mail without problem under DOT exemption 7887 as "Flammable Solids." (It is interesting to note that fireworks must be shipped as "Class C Explosives.") Even the British government (notorious for its anti-things-that-contain-propellant laws) has determined that the current range of engines may be used without restrictions, save those pertaining to general safety.

As supplied, the model rocket engines comply with U.S. Consumer Product Safety Commission standards, and the launching of model rockets has been exempted from regulation by the Federal Aviation Agency. This relates to "unmodified" rockets, of course!

The techniques discussed in this manual are cheap and cheerful. They have been found to work but are not necessarily the "correct" or established way of doing things.

CHAPTER 2

PRINCIPLES OF OPERATION



Rockets are propelled according to Newton's third law of motion: for every action there is an equal and opposite reaction.

The burning fuel creates gases much greater in volume than the fuel itself. As gas escapes through the engine nozzle, it exerts an equal force in the opposite direction, thrusting the rocket forward. The rocket is not (as one might at first think) propelled by the gas pushing against the air.

The supply of gas is provided by a small "solid-fuel" engine mounted in the base of the rocket. The propellants most typically used will be either black powder or ammonium perchlorate. Typical percentage-by-weight mixes of both propellants are:

Black powder: 74 percent KNO_3 (oxidizer), 15.6 percent C, 10.4 percent S (fuel plus binder).
Ammonium perchlorate: 82 percent NH_4ClO_4, 17 percent synthetic rubber (fuel/binder), 1 percent burn-rate enhancers.

In addition to the propellant, most commercial engines incorporate a smoke charge (to help track the rocket during its nonpowered coast phase) and an ejection charge. Thus there is a delay—the length of which is determined by the amount of smoke charge present—between the end of the propellant burn period and the ejecting of the nose cone and parachute.

The rocket engine is fired by means of an electrical igniter. This is inserted into the engine nozzle so as to contact the propellant therein. It is initiated via a 6-volt battery pack and is, essentially, a "slow"-burning electrical match.

The most commonly available engines are rated by the manufacturers by total power produced, average thrust in newtons (4.45 newtons = 1 pound), and the number of seconds between the end of the thrust and (where applicable) the ejection charge. The rating takes the form of a three-character alphanumeric "serial number."

Thus, a "B6-4" engine will have twice the total power of an "A" designated engine (and half that of a "C" engine), will have an average thrust of 6 newtons, and will incorporate a delay of four seconds between the end of the thrust period and the firing of the ejection charge. Engines with a "0" suffix have no smoke or ejection charge and can be coupled directly to other engines to provide a multistage rocket.

Engines are available in the ranges "A" to "D." Important applicable specifications are given for various engines in subsequent chapters.

The engine is installed in a simple cylindrical mount which itself is affixed to the inside base of the rocket. The mount may incorporate a small, spring-steel quick-release device, or it may simply be held on a friction-fit basis. The securing technique need not be complex, as the tendency of the engine/s, once ignited, is to push upward anyway.

The centering/support rings of the engine mount have an external diameter similar to the internal diameter of the rocket body and are secured with adhesive. The engine tube has an internal diameter very slightly larger than that of the engine it is intended to carry.

A washerlike stop piece is installed inside the tube, and it is against this that the shoulders of the engine rest when inserted. Gases from the ejection charge are free to pass through its hollow center.

LAUNCHING

The rockets are launched (conventionally) from a com-

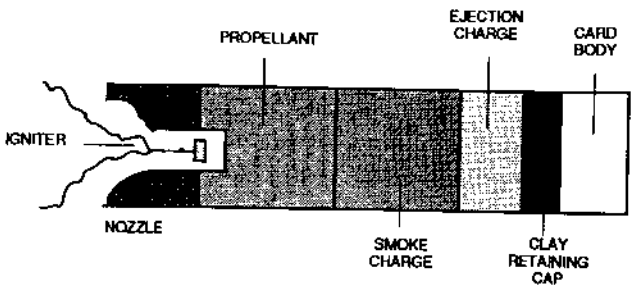


Figure 1. *Typical model rocket engine.*

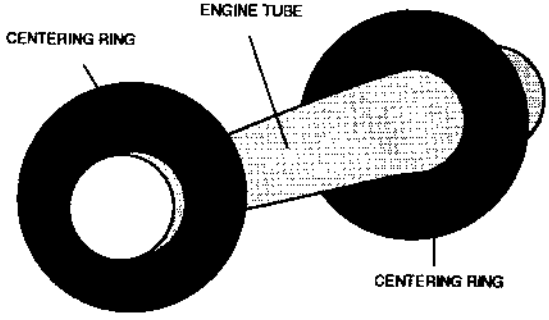


Figure 2. *Engine mount.*

mercially available launch pad. The pad is comprised of a stand, a metal deflector plate, and a vertical launch rod. The stand has an adjustable head to facilitate aiming and will not permit tilting in excess of 30 degrees from the vertical for safety reasons.

A cylindrical standoff piece is used to hold the rocket base/igniter wires clear of the deflector plate during firing. This can be improvised by wrapping tape around the launch rod.

The rod engages with rocket-mounted launch lugs and provides stability during the first couple of feet of flight. The

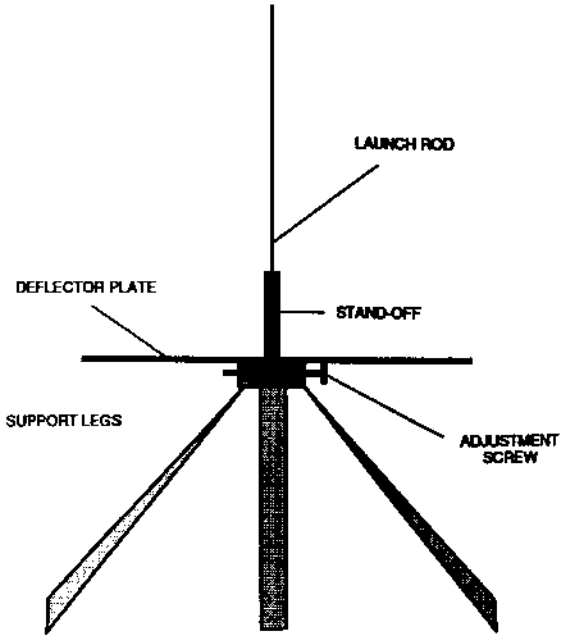


Figure 3. Typical commercial launch pad.

deflector plate merely serves to prevent ground fires being caused by the engine exhaust.

When firing explosive pad-launched rockets, the type of pad shown in Figure 4 should be used. It incorporates two launch rods and weighted or staked support legs for far greater stability.

The extra launch rod requires an additional set of launch lugs affixed to the rocket body. These should be attached 180 degrees from and exactly opposite the originals.

TYPICAL ROCKET

In a commercial rocket, the shock cord is a length of elastic

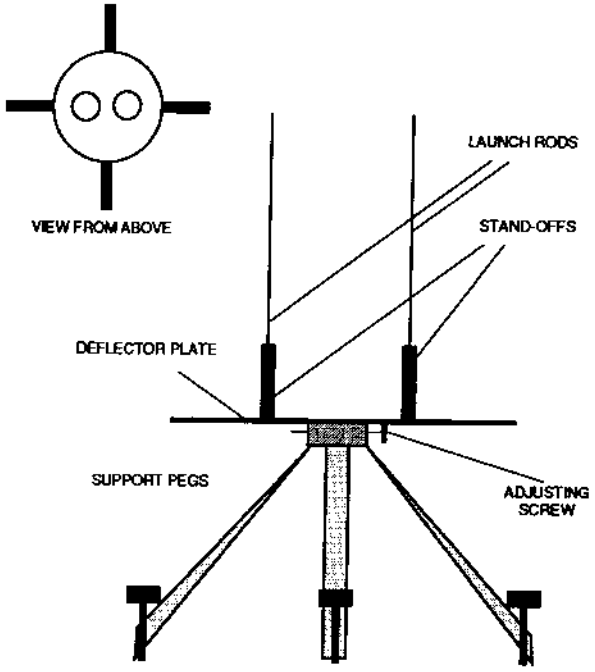


Figure 4. Improvised launch pad.

connected between the rocket body tube and the parachute lug. It takes the shock during nose-cone ejection and keeps the nose cone and rocket body together for recovery.

When preparing the rocket for a launch, recovery wadding is packed loosely into the body tube to a depth approximately three times the body diameter. The fire-resistant wadding protects the chute from damage from the ejection charge and provides some additional pressure resistance to ensure the chute and cone are ejected cleanly.

With the wadding in place, the parachute canopy is fold-

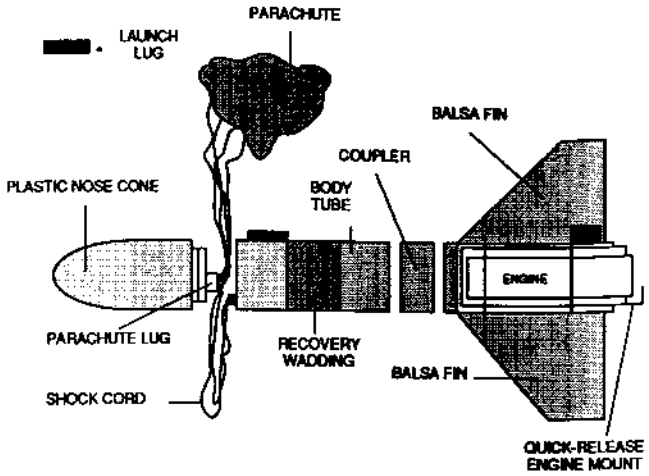


Figure 5. Typical rocket.

ed and the lines wrapped loosely around it. The chute and shock cord are placed in the body tube and the nose cone installed. The nose cone normally will be a sliding fit in the body tube.

In the case of modified rockets not intended for recovery, the chute, shock cord, and recovery wadding will be discarded and the nose cone secured with adhesive. Where an explosive warhead is to be ejected, however, the wadding will be retained and the nose cone installed on the usual friction-fit basis. Note again that when firing explosive missiles, additional launch lugs should be attached and the improvised launch pad with its two launch rods used.

LAUNCH CONTROLLER

A launch controller enabling remote launches should always be used, regardless of whether conventional or modified rockets are being fired. The system should be based around a switch that returns to "off" automatically when released and should include a removable safety key (which can be as simple as a bent nail) that must be inserted manually into the controller to render the electrical circuit complete.

A visual indication that the circuit is complete should also be included, and a bulb in series with the safety lock achieves this. A commercial controller is available that meets these requirements; it can be purchased separately or as part of a "starter kit" that also comes with a launch pad.

To launch a rocket, an engine of the required size is installed in the base of the rocket and an igniter inserted into the nozzle. The igniter may be secured with masking tape.

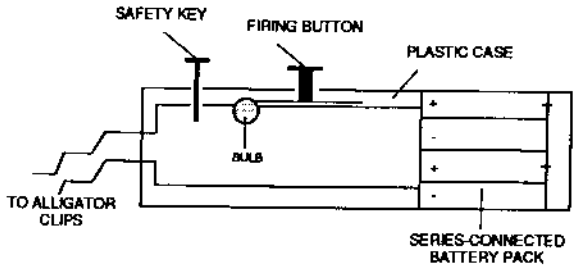


Figure 6. Typical launch controller.

The rocket is now lowered onto the launch pad rod until it rests upon the standoff piece.

It is worth noting that the vast majority of misfires are caused by either a faulty or poorly installed igniter. Therefore, the igniter should be physically checked for damage before installation. If it is okay, it is inserted into the nozzle until resistance (from the solid propellant) is felt.

If the controller safety key is not in place, the controller wires may be attached to the igniter.

The safety key may now be inserted (at which point the indicator light should glow). With the immediate area clear of personnel, the rocket can be fired. Four 1.5-volt AA cells are sufficient to fire the igniter.

TYPICAL FLIGHT PROFILE, SINGLE STAGE AND MULTISTAGE

The flight profile of an unmodified model rocket commences when the igniter fires. When this happens, the rocket engine begins to burn and the rocket lifts off.

The rocket accelerates skyward at great speed. Speeds of several hundred miles per hour can be reached in a matter of seconds, depending on the power/weight ratio of the engine/rocket.

Having consumed the available propellant, the rocket continues toward its peak altitude under its own momentum, discharging smoke for observation purposes. Several seconds later the smoke charge ignites the ejection charge. The nose cone is blown off and the chute pulled free. The chute fills with air and the rocket body and nose cone drift back to earth.

In a multistage rocket, the first-stage engine will have no smoke or ejection charge. Instead, it provides the initial liftoff and thrust power and then ignites the second stage engine. As each subsequent engine fires, the previous one, complete with its mount and body-tube/fin section, is jettisoned. The final (upper) stage engine is the only one with an ejection charge, and when this is reached, the sequence of events is as per the single-stage rocket.

As can be seen from the chart (a more complete version of which is found in engine manufacturers' catalogs), each engine has a lift capacity determined, other things being equal, by the amount of propellant vs. smoke charge (delay time = smoke charge) it contains.

Note that when selecting engines for use in a specific project, the engine weight should be added to that of the rocket and payload to determine total launch weight.

Other things being equal, the greater the "headroom" between the maximum lift capacity of a given engine and the actual weight of the rocket, the greater the height/range achieved.

Always test for height/range capabilities in an isolated area using inert components of the same weight and in the same position/configuration as any explosive material/firing-

ENGINE SPECIFICATIONS

TYPE	DELAY	MAX LIFT WEIGHT	THRUST DURATION	WEIGHT
B6-2	2.00 sec.	4.50 oz.	0.83 sec.	0.68 oz.
B6-4	4.00 sec.	4.00 oz.	0.83 sec.	0.71 oz.
B8-5	5.00 sec.	5.00 oz.	0.60 sec.	0.68 oz.
C5-3	3.00 sec.	8.00 oz.	2.10 sec.	0.90 oz.
C6-5	5.00 sec.	4.00 oz.	1.70 sec.	0.91 oz.
B6-0	0.00 sec.	4.00 oz.	0.80 sec.	0.58 oz.
C6-0	0.00 sec.	4.00 oz.	1.68 sec.	0.80 oz.
D12-0	0.00 sec.	14.00 oz.	1.70 sec.	1.44 oz.
D12-3	3.00 sec.	14.00 oz.	1.70 sec.	1.49 oz.
D12-5	5.00 sec.	10.00 oz.	1.70 sec.	1.52 oz.
D12-7	7.00 sec.	8.00 oz.	1.70 sec.	1.55 oz.

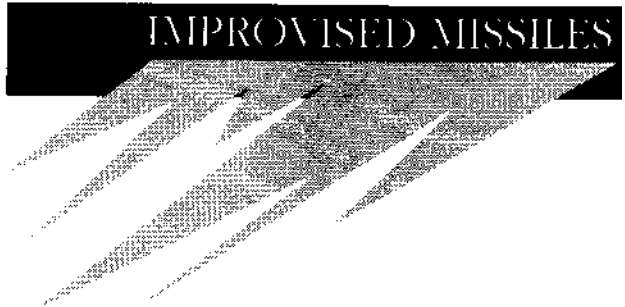
"B" and "C" engines are 2.75 inches long, 0.690 inch in diameter.
"D" engines are 2.75 inches long, 0.945 inch in diameter.

chain components that will be used subsequently.

Always fire modified/explosive rockets from behind cover.

CHAPTER 3

IMPROVISED MISSILES



The designs that follow (Chapter 5) are based on commercially available, preformed rocket kit parts. These are available from most hobby/model shops and via mail order. If you are unfamiliar with the field, a visit to the local hobby/toy store is a must.

Specific brand names have not been given for legal reasons, but the reader should have no trouble determining (via reference to available catalogs, kits, and components) those which meet the parameters outlined in subsequent pages.

In any event, all the parts can be improvised easily. Cardboard tubes can be salvaged from many sources, balsa fin stock can be purchased in sheets from craft and hobby shops, and plastic nose cones can be improvised from the caps of aerosol spray cans and bathroom products.

TESTING FOR FLIGHT STABILITY

The stability of all improvised rockets—or commercial rockets into which extra parts have been added—must be checked and alterations made as required before firing. Flight stability can be determined by installing all components and engines (in the case of explosive rockets, inert components of the same weight and installed as per the explosive and fuze items should be used) and then locating the rocket's center of gravity.

A simple way of doing this is to find the point along the

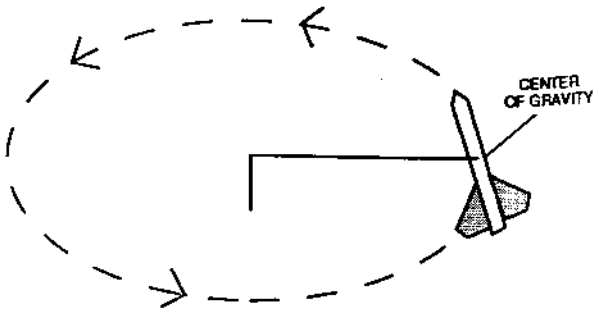


Figure 7. *Testing for flight stability.*

body at which the rocket can be balanced on the edge of a ruler and attach a thin cord some 6 feet in length to this point. Whirl the rocket around by the cord at eye level and confirm that the rocket "flight path" is straight and true. Make small adjustments to the fin positions and/or the distribution of internal components as required.

Accurate fin placement is made easier if glue is applied to both the fin edge and the appropriate part of the body tube and left to dry for about five minutes before assembling. A commercial device is available that holds fins in position while the glue dries.

ENGINE MODIFICATION TECHNIQUES

The simplest modification that can be made to commercial rockets in order to obtain greater ranges and/or a higher payload capability is to utilize a much more powerful engine than is recommended by the manufacturers. For example, one can install a "D" engine in a rocket intended to use only "B" or "C" engines. This will require replacement of the supplied engine-mount assembly with one of a larger diameter, although often the engine-mount requirement can be ignored completely and the engine secured on a friction-fit basis by wrapping it with tape.

As long as the engine can be mounted securely, centrally, and in such a manner that the stability of the rocket in flight is

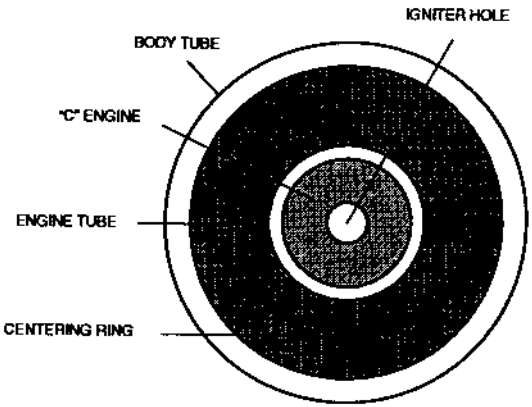


Figure 8. *Rear view of conventional "C" engine installation. The engine will be either a "0" suffix type or one that incorporates a delay, according to the project requirements.*

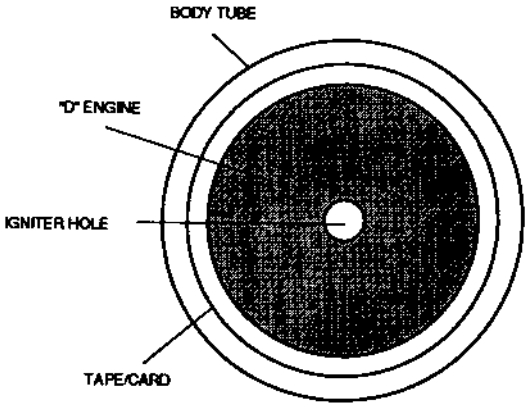


Figure 9. *Rear view of "D" engine replacement. The existing engine, centering/support rings, and engine tube have been removed, and the "D" engine's diameter has been increased to create a friction fit within the rocket body itself.*

not adversely affected, then any form of improvisation may be used to accomplish the modification. Thus tape, adhesive, and silicone sealant may all be pressed into service.

Another technique is to install an additional "0" suffix engine (or more than one, of course) to provide a longer burn time, affixing it to the top of the first engine with wood glue applied to the card rim only (more on card adapters later). Cut off and discard the empty end sections of both engine bodies, and rotate the second engine 180 degrees, as shown in Figure 10.

The uppermost nozzle may now be removed by scraping with a plastic or wooden tool, or the nozzle hole can be enlarged to accommodate a fuse, black powder, etc.

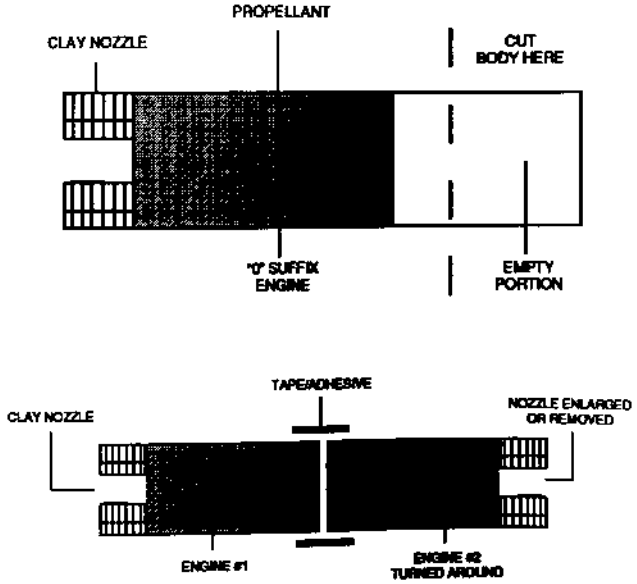


Figure 10. Adding extra engines.

The lengthened engine can be installed by extending the original engine mounting tube or discarding the engine mount and wrapping tape around the engine bodies to obtain a friction fit.

A higher initial thrust can be obtained from any flat-ended engine by carefully boring out a central cavity from the propellant material. The cavity should be around one-third the diameter of the propellant block and extend inward some five times that diameter. Never use any high-speed drill or other tool or technique that will generate excessive heat. A small hand reamer works well.

MULTISTAGING

Ranges can be increased by using multistage rockets. These incorporate individual engine, body section, and fin assemblies that are jettisoned when the next engine in the series fires.

Stage coupling is accomplished by using card adapters. These take the form of a collar with an external diameter slightly less than the internal diameter of the body tubes themselves, thus allowing a sliding fit. An adapter is secured with adhesive at the base of all the stages (except the first) in such a manner that half of its length remains exposed, and the preceding stage is simply slid on.

Prior to installation, the engines are coupled using cellophane tape. As the engine in the next stage ignites, the

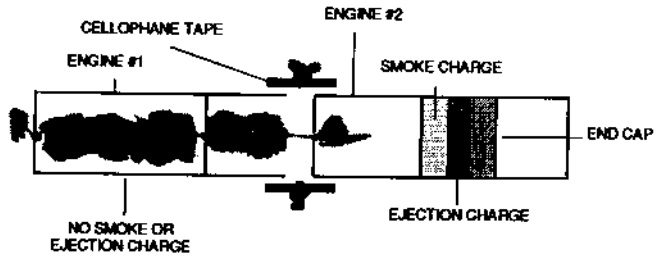


Figure 11. Engine connection technique.

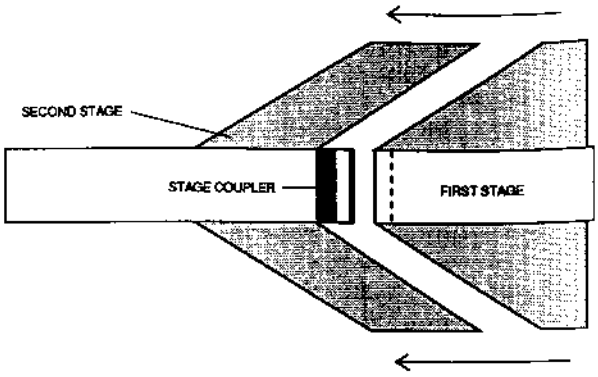


Figure 12. Two-stage rocket.

resulting fire and pressure simply burn the tape through and jettison the entire lower engine/body/fin assembly.

All engines except the final (upper stage) one are to be of the "0" suffix type. The upper-stage engine is selected according to the constructor's requirements.

Existing single-stage rockets can be converted into multistage devices by adding extra body tube sections, each of which contains an engine mount assembly, or by segmenting an existing length of body tube and turning the sections into separate stages. Some commercial multistage rockets are available.

The fins on each additional body piece can be designed to mate and thereby form a continuation of those on the subsequent stage, or they may be duplicates of the existing fins. In either case, they should be aligned during fitting.

The stage couplers must have a diameter that produces a friction fit inside the appropriate body tube, and a length of approximately .75 to 3.9 inches, depending on the rocket body diameter. The larger the diameter, the larger the coupler.

"POWER-IN" MODIFICATION

This variation on standard techniques causes the rocket to power downward into the ground at tremendous speed

rather than falling under the force of gravity. It has to be seen to be believed!

Couple two engines as per Figure 10, except that here the first-stage engine incorporates a delay rather than being a "0" suffix unit. Other things being equal, best effects are obtained when the delay selected is the maximum available.

Remove the clay retaining cap and ejection charge material from the lower engine by scraping with a plastic or wooden tool, leaving only the solid propellant and smoke charges. There is only a tiny amount of ejection charge compared to smoke charge, and the smoke charge itself is of a lighter, gray color. Shake out all loose material before attaching to the other engine.

Upon launching, the rocket travels under the power of the first engine until the propellant is exhausted. At this point the smoke charge fires and the rocket slows. After a few seconds the rocket begins to fall nose down. The smoke charge now ignites the second engine, which fires, causing the rocket to accelerate again.

Depending on the height that the rocket achieved initially, the second engine frequently will still be burning propellant when the rocket hits. It will almost certainly still have

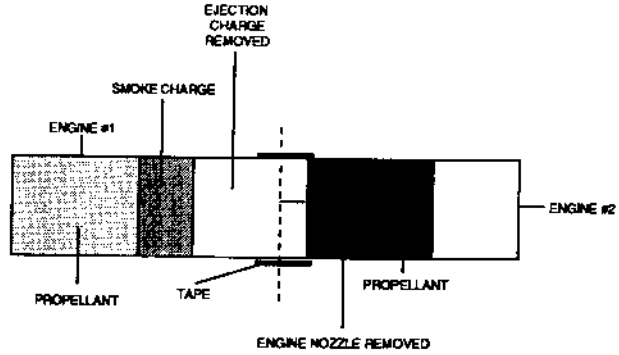


Figure 13. "Power-in" engine connection technique.

unburned smoke and ejection charges. These can be incorporated into the firing chain of an explosive missile with great effect.

ULTRA-POWER CUSTOM ENGINE

All work on this modification is to be undertaken outside. Protective goggles and gloves must be worn. Have water or an extinguisher on hand in case of fire.

Disassemble seven "0" suffix engines by cutting lengthwise into each card body in such a manner that the card can be peeled away and the propellant block removed.

The clay nozzles are now broken away and discarded. It does not matter if small bits of the clay remain, as all but one of the sticks (use this one as the central stick) will be rotated

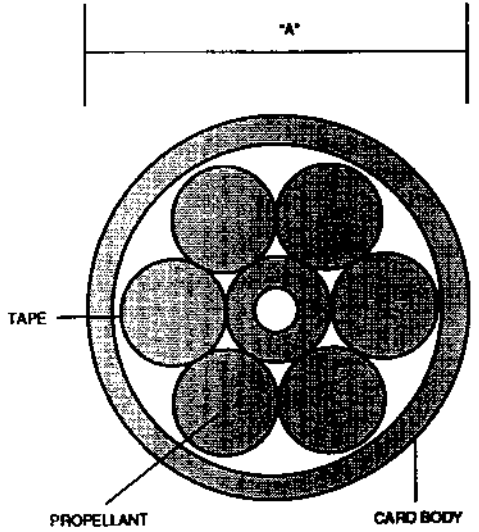


Figure 14. Custom engine viewed from below.

prior to assembly so that the nozzle ends become the top of the engine pack.

Assemble the propellant blocks into a bundle as shown in Figure 14 and secure with tape. Install the bundle in a card tube having a diameter that facilitates a friction fit and a length that produces a gap of about 1 inch at either end. The wall thickness of the tube should be about be 3 to 5 millimeters.

An improvised nozzle can now be prepared and installed in one end of the tube. Prior to installation, sprinkle a small amount of black or smokeless powder onto the propellant sticks simply to help ensure ignition.

For once-only use, the nozzle can be made from modeling clay or a "plastic metal" type material, or a hardwood nozzle of the required dimensions can be made and sprayed

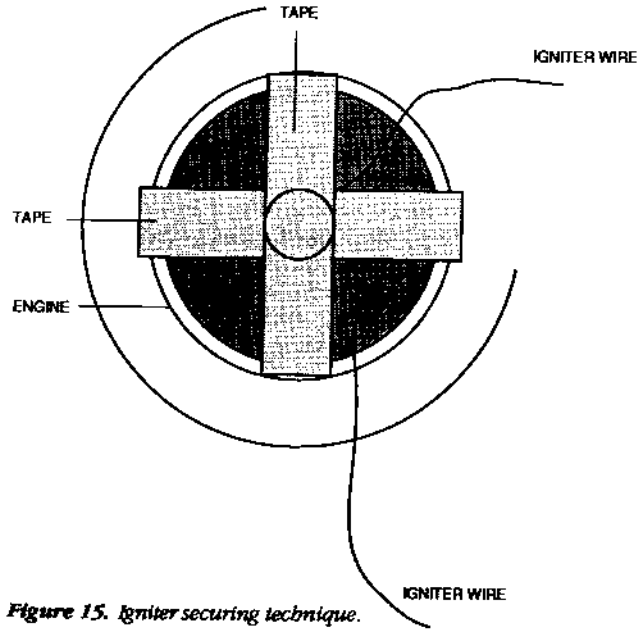


Figure 15. Igniter securing technique.

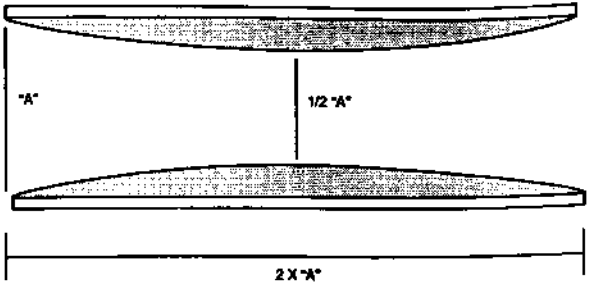


Figure 16. *Improvised nozzle in cross-section.*

over with high-temperature paint available from vehicle accessory shops. The burn time of most improvised engines will be so short anyway that by the time the nozzle has been destroyed, its job will have been done.

Whatever method is employed, the nozzle should be pressed home firmly against the propellant sticks and, if necessary, secured with adhesive applied to the outer wall of the nozzle only.

With the nozzle in place, pour a very small amount of black or smokeless powder into the nozzle opening and install an igniter. Secure the igniter with masking tape in such a manner that neither it, nor any of the powder, can fall out. The best technique is shown in Figure 15.

The choke point at the center of the nozzle is half of the mouth diameter, and the angle of divergence/convergence of the nozzle mouths is around 30 degrees.

Custom engines may also be coupled in-line to provide both greater lift capability and range.

CHAPTER 4

WARHEAD SAFETY

Having *first* determined through test-firing with nonexplosive components the optimum warhead/payload weight that the rocket will carry over the required distance, the material used for test purposes can be replaced with an equivalent weight of similarly distributed explosive/firing-chain components and the recovery system components discarded. The precise specifications of firing-chain components and the weight/type of explosive material used will vary according to the type of rocket employed.

In direct contrast to the safety considerations outlined in the "Model Rocket Safety Code" (which are intended to prevent rockets from traveling horizontally), it is recommended that the *minimum* angle of launch when firing improvised missiles be *10 degrees from the vertical*. The *maximum* angle of launch, applicable especially to shoulder-fired devices, should be slightly less than *90 degrees from the vertical* to allow for any drop when the missile leaves the tube.

In the designs in the following chapter, the nose cones are of the commercial plastic type. It can be assumed that, where necessary, the bottom sections of these have been removed to facilitate access. Similarly, where a reference appears to, for example, the smoke charge lighting a fuse, it can be assumed that the retaining cap and ejection charge material have first been removed.

That said, the following improvised safety features (or

some other variants serving the same purpose) must be incorporated into all explosive rocket configurations. These systems are not shown on the warhead/rocket designs themselves for reasons of clarity.

ELECTRICAL SAFETY

This device provides for safer handling and protects against premature detonation in the event that an explosive impact-firing missile is dropped. The firing circuit is not actually armed until the missile is safely on the pad or in the tube.

The switch employed is of the subminiature release-to-make/release-to-break type. This type of switch is turned "on" by depressing and then releasing the button and turned "off" in the same manner. The release action is the one that actually causes the state of the switch to alter. These are readily available from the usual outlets.

The switch is installed in the rocket body in the "off" position in such a manner that it can be operated externally via a small piece of dowel inserted through an access hole in the rocket body and, where applicable, launching tube wall. In the case of tube-launched missiles, the access holes will align if, during construction, the rocket is installed in the tube and a hole drilled simultaneously through both launcher and rocket walls.

After loading, the dowel piece is inserted and the switch depressed and released. The system is now live.

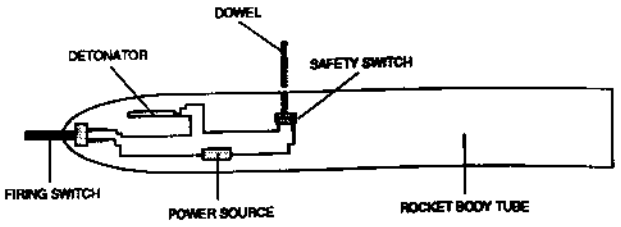


Figure 17. Manual electrical safety.

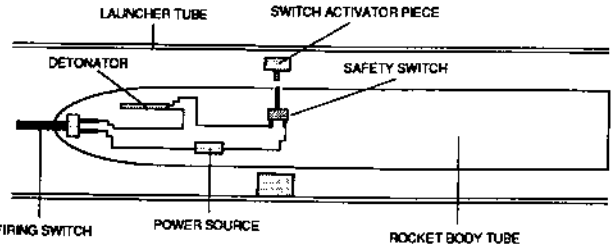


Figure 18. Automatic electrical safety.

For tube-launched missiles, the dowel piece may instead be incorporated into the inner face of a discarding support piece in such a manner that it depresses the switch when installed during loading (see Figure 18). The switch remains depressed until the support piece is discarded when the missile leaves the tube, at which point the switch springs out to the "on" position.

MECHANICAL SAFETY

This safety feature can be incorporated into striker/plunger-

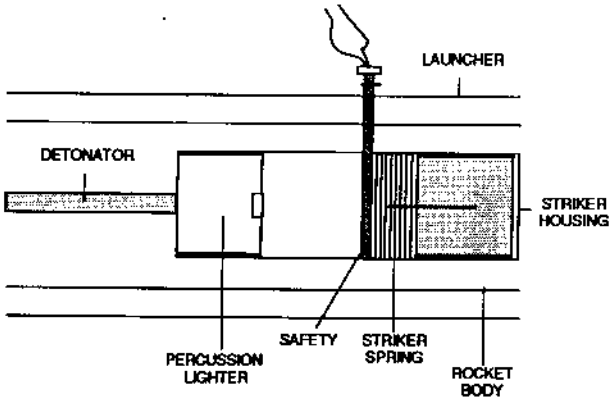


Figure 19. Manual mechanical safety.

type firing mechanisms. It consists, simply, of a wooden or plastic pin inserted through the missile wall in such a manner that it prevents the striker/plunger from contacting the primer or completing an electrical circuit.

In the case of pad-launched missiles, this safety is removed manually immediately prior to launching. For tube-launched missiles, the safety may incorporate a spring that is compressed during loading and kept under tension by the launcher walls. Upon leaving the tube, the spring throws the safety pin free (see Figure 20).

A clip safety takes the form of a simple split-washer or such that fits between a nose-mounted plunger and the nose cone proper, preventing the former from being depressed.

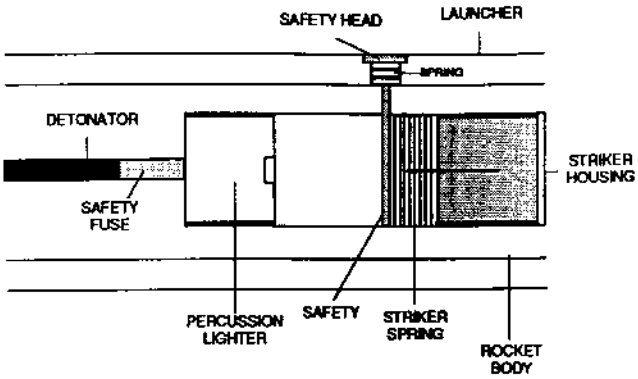


Figure 20. Automatic mechanical safety.

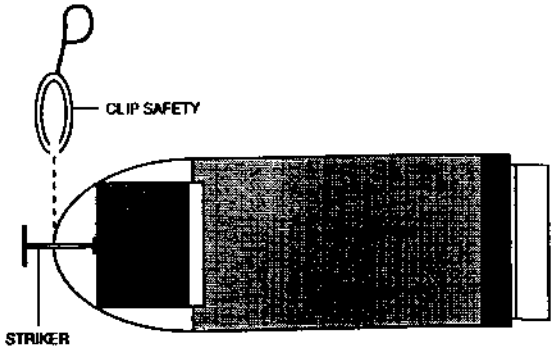


Figure 21. Clip-type safety.

CHAPTER 5

WARHEAD DESIGNS

The percussion fuzes shown in several of the following designs operate only when the missile strikes an object at speed. When this occurs, the sudden loss of momentum causes the striker (which is free to slide within its housing) to be thrown forward. This forward movement overcomes the tension in the spring and the striker pin hits the primer. The spring must be of sufficient strength to prevent the striker pin from contacting the primer when the missile is inverted during normal handling.

As a matter of prudence, safety fuse should be used in the firing chain of nonelectric, impact-firing devices.

Improvised explosive warheads should only be assembled immediately prior to use.

IMPACT FIRING I

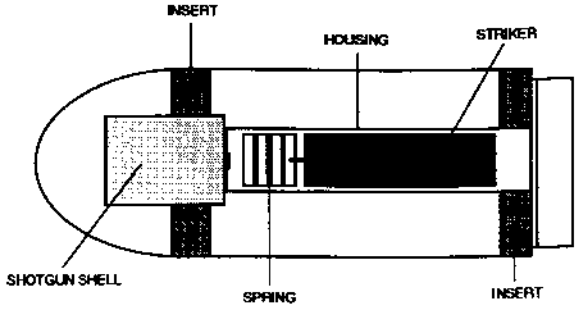


Figure 22.

Upon impact, the striker flies forward and hits the shell primer, causing the shell to fire.

IMPACT FIRING II

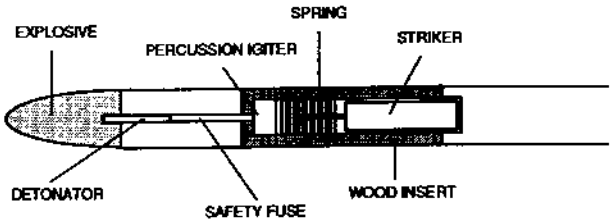


Figure 23.

Upon impact, the striker hits the primer, lighting the percussion igniter and thereby the safety fuse. After a few seconds, the burning fuse reaches the blasting cap, which explodes and detonates the warhead.

IMPACT FIRING III

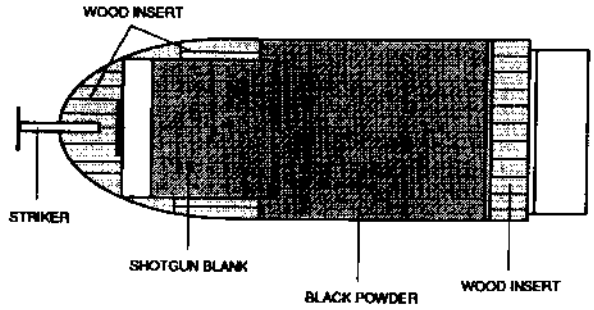


Figure 24.

Upon impact, the striker sets off the shotgun blank, igniting the black powder and producing a low-level explosion.

IMPACT FIRING IV

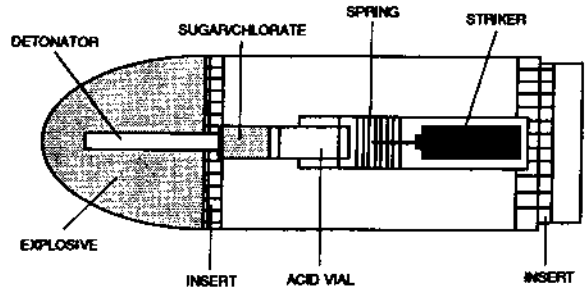


Figure 25.

Upon impact, the striker shatters the glass vial, causing the acid to contact the potassium chlorate/sugar mixture. The resulting heat and flame fire the detonator.

IMPACT FIRING V

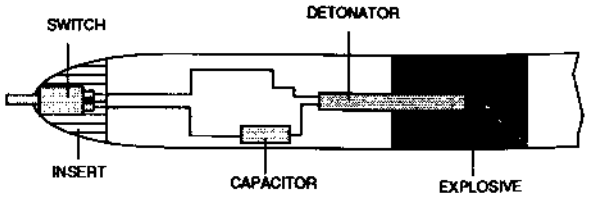


Figure 26.

The charged capacitor is used, as its weight is far less than that of a battery. It is charged immediately prior to installation.

Upon impact, the switch, which is of the press-to-make/press-to-break type, is depressed and the electrical circuit completed. Current flows from the capacitor to the detonator and the device explodes.

IMPACT FIRING VI (SHAPED CHARGE)

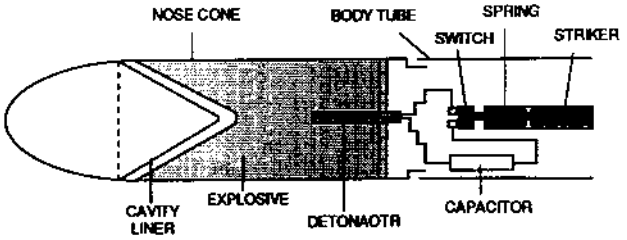


Figure 27.

Ideally, the nose cone should be of a lightweight metal having a thickness 1 millimeter or so greater than the thickness of the internal cone. Similarly, the distance between the front of the nose cone and the face of the cavity should be one to two times the diameter of the cone (cavity) face.

The cavity liner is made of copper or tin sheet, 1 to 3 millimeters thick, formed into a cone (as shown in Figure 27), with an angle of between 30 and 60 degrees.

The electrical detonator is positioned at the top center of the explosive. The capacitor is of the electrolytic type.

Upon impact, the sliding plunger hits the switch, which closes, completing the circuit and firing the detonator. The cavity/liner "focuses" the explosion, creating a highly penetrating effect.

The cone can also be improvised from a wine glass or funnel. If a cavity liner can not be improvised, lesser shaped-charge effects may be obtained by simply cutting the cavity directly out of the explosive material itself.

IMPACT FIRING VII (SMOKE)

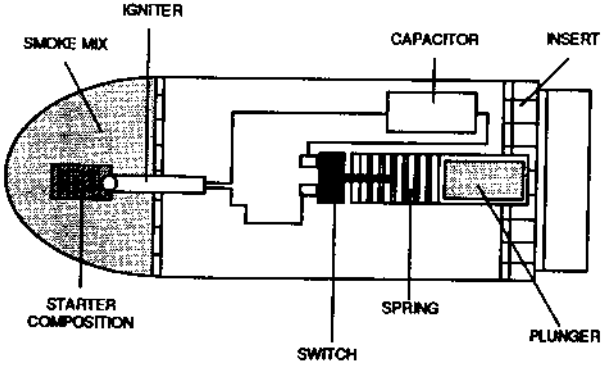


Figure 28.

Upon impact, the sliding weight is thrown against the switch, completing the electrical circuit and firing the smoke charge.

IMPACT FIRING VIII

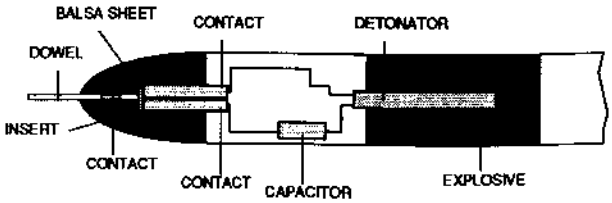


Figure 29.

Upon impact, the dowel is depressed and the contacts touch. This completes the circuit; current flows from the capacitor to the detonator and the device fires.

A battery can be substituted for the capacitor if tests (using nonexplosive components) confirm that the rocket/ engine configuration can handle the weight. The dowel should be tightly fit in the nose cone. The dowel contact may be foil or conductive silver paint.

The balsa sheet prevents the dowel piece from operating the switch except under force of an impact.

INCENDIARY I

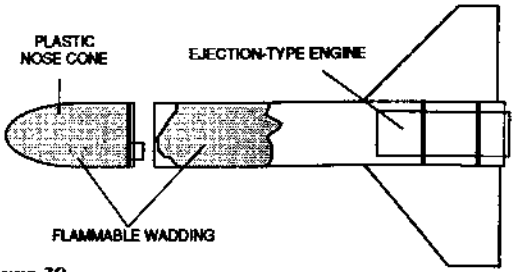


Figure 30.

At the end of the propellant and smoke charge burn period, the ejection charge ignites and discharges the flammable wadding, which floats down onto the target.

INCENDIARY II

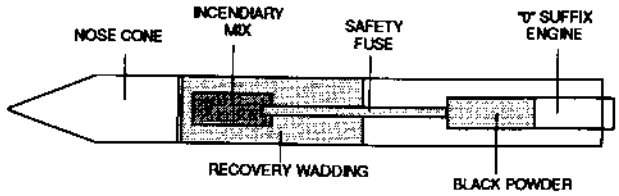


Figure 31.

A cylindrical extension piece is added to the end of the engine and a small quantity of black or smokeless powder poured in. The safety fuse is inserted into this and secured with tape. The surrounding rocket body space is packed with recovery wadding as shown.

The ejection charge simultaneously ejects the nose cone and starts the safety fuse burning, subsequently igniting the improvised incendiary mix in its container. The engine end of the fuse should be split and a match head inserted to assist lighting.

AIRBURST I

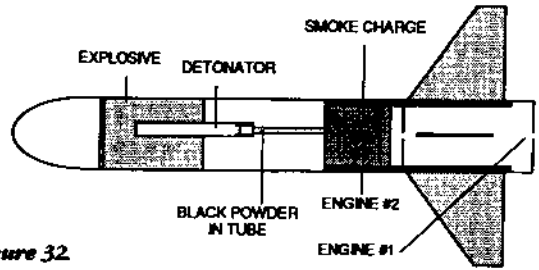


Figure 32.

The clay retaining cap is removed from the engine and loose material discarded. A powder-filled tube is secured in the resulting space. The end of the burning smoke charge ignites the black powder in the tube, which flashes through to the detonator.

AIRBURST II

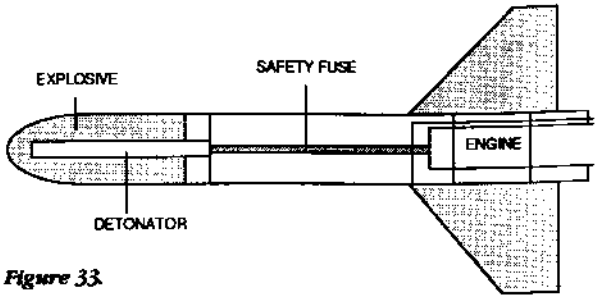


Figure 33.

The smoke charge lights the safety fuse, which, after a predetermined delay, sets off the blasting cap, which detonates the explosive. The length of the safety fuse determines the height above the ground at which the warhead explodes.

AIRBURST III

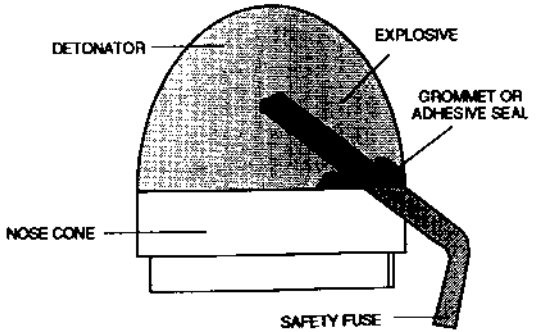


Figure 34.

The safety fuse is lit and the rocket launched. The device explodes when the burning fuse reaches the detonator.

AIRBURST IV

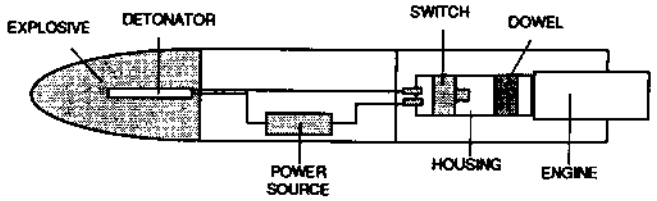


Figure 35.

The ejection charge forces the dowel piece against the switch, which completes the electrical circuit, causing the detonator to fire.

AIRBURST V

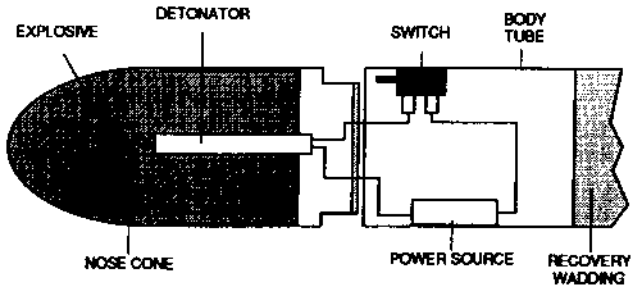


Figure 36.

When the ejection charge fires, the nose cone is blown free and the switch released. The electrical circuit is completed and the warhead explodes.

The switch, which is of the release-to-make/break type, is secured firmly with epoxy in such a manner that it is depressed when the nose cone is inserted. The power source may be an electrolytic capacitor or a battery.

DELAYED-ACTION DEVICE

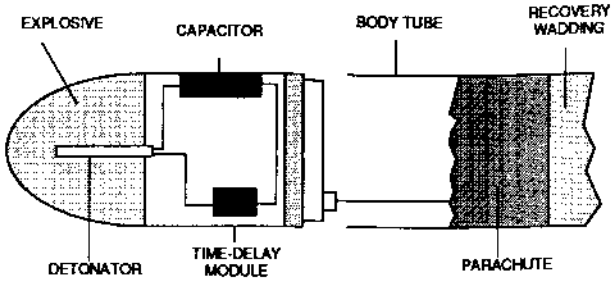


Figure 37.

Again, an engine incorporating an ejection charge is used here. Upon firing, the nose cone with its explosive components is discharged and the parachute deployed. The warhead floats to earth and explodes after the preset time delay expires.

Note that with all such projects involving parachutes, wind drift is a major consideration. Tests (using inert components) will enable you, however, to compensate for anticipated drift caused by a given wind speed and direction with surprising accuracy.

SHOULDER LAUNCHER I

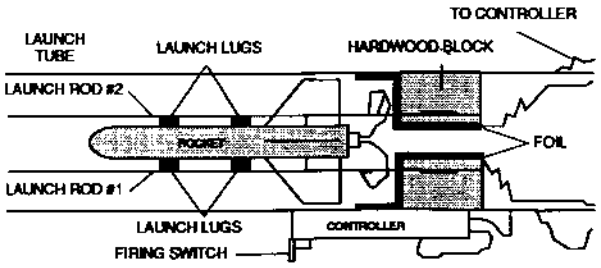


Figure 38. Sectional view showing construction details.

Never fire safety-fuse-based missiles from an improvised shoulder launcher. If the missile hangs up in the tube and you are slow with your immediate-action (IA) drills, your hair will really get messed up.

Q: What are the IA drills for this type of weapon?

A: In the event of any malfunction, place the weapon on the ground at a speed approaching that of light and run like hell!

The rocket to be used in this configuration is first equipped with an additional pair of launch lugs. These are attached to the opposite side of the rocket body, as shown in Figure 38.

The launch tube is cardboard or plastic, three to four times the length of the rocket. The switch is of the nonlatching type.

To prepare for firing, install an igniter in the rocket nozzle and secure it ***firmly*** with masking tape. Spread the igniter wires so as to ensure contact with the foil pieces.

Now slide the rocket down into the tube. To fire, place the rocket tube on the shoulder and, having checked that no one is standing immediately to the rear, depress the switch.

Note that there may be a delay of about a second before the rocket engine fires (depending on the state of charge of the battery pack), so a good follow-through is essential!

Take care not to point the launcher downward in such a manner that an impact-firing rocket could fall from the tube and explode.

Note that for maximum effect with all shoulder-launched impact-firing missiles, targets should be engaged from the closest practicable range, and certainly within a distance no greater than two-thirds of the missile's determined maximum range.

A simple sight can be improvised using nonexplosive components during tests. This may take the form of a short tube mounted on the top of the launcher, with thin string fastened across its front, as shown in Figure 39.

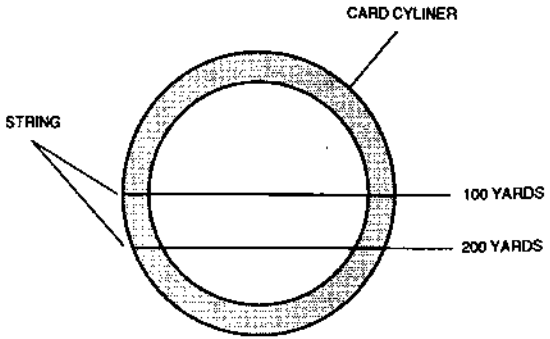


Figure 39. *Improvised sight.*

Start with a basic cross hair and aim at some object dead center. Note the drop, any windage effects, and the actual "hit" area. Note the range on the side of the launcher in felt pen. If required, a second cross hair can be added below the first and its corresponding range noted.

Be aware that with a "D" prefix engine, the shoulder-launched missile described in the next chapter will travel many hundreds of yards, even with the added weight of firing-chain components. Whilst this might seem like overkill for a missile with an obviously low explosive capacity, the idea is that at closer ranges, targets can be engaged with surprising accuracy and "kill confidence." This latter condition is by virtue of the fact that the still high speed of the missile will help ensure the correct operation of impact-fired mechanisms.

SHOULDER LAUNCHER II

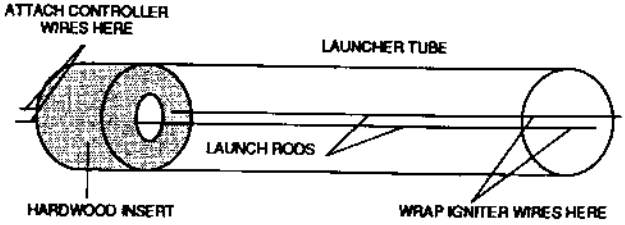


Figure 40. *Sectional view showing protruding launch rods.*

The launch rods in this device extend an inch or so through the rear of the hardwood insert so an electrical connection can be made through them to the igniter.

To load, hold the rocket tube vertically and engage the launch lugs with the launch rods. Wrap the igniter wires tightly around the launch rods and push the rocket home using a hollow tube of such a diameter that it rests on, but will not slide over, the rocket shoulders.

Attach a commercial launch controller—or an improvised version—to the top of the launcher tube with duct tape, or attach a battery pack and nonlatching switch assembly to the underside of the launcher as per the previous design. Connect the alligator clips from the controller to the ends of the launch rods.

The upright portion of a scrap computer joystick can be used to make a very professional-looking firing switch/pistol grip. Computer game "light guns" are also ideal, as these incorporate a built-in battery holder.

SHOULDER LAUNCHER III

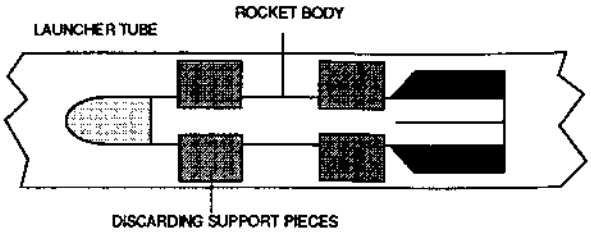


Figure 41. Sectional view showing discarding support pieces.

Additional launch lugs are not required for this design.

The discarding support pieces are two disks, 1 to 2 inches thick, of felt or balsa wood, for example. Each disk has an internal diameter similar to that of the rocket body and an external diameter that allows a sliding fit in the rocket tube. The disks are cut in half and mated around the rocket body during loading, as shown in Figure 41. The electrical connections are the same as for Shoulder Launcher I.

To load, install an igniter and secure with masking tape.

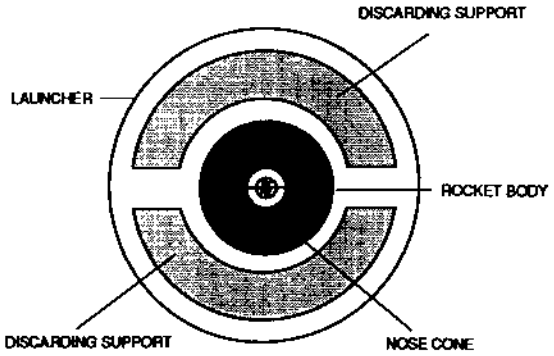


Figure 42. Front view of missile in tube.

Again, ensure the ends of the igniter wires are bent so as to provide a good electrical contact with the foil.

The lower (engine end) pair of disks is then placed around the rocket body and the body lowered partway into the tube. The upper (nose cone end) pair of disks is now fitted onto the rocket body and the rocket pushed home.

Attach the launch controller alligator clips to the ends of the foil contacts, install the safety key, and confirm continuity. Depressing the controller button fires the rocket, which, upon leaving the tube, discards the support pieces.

MLRS (MULTIPLE LAUNCH ROCKET SYSTEM)

The rocket tube assembly consists of, for example, twelve card or plastic tubes, assembled as per the Shoulder Launcher II design and secured with masking tape, as shown in Figure 43.

To ensure simultaneous firing, a battery pack having a high current capacity should be used. A car or motorcycle battery is ideal.

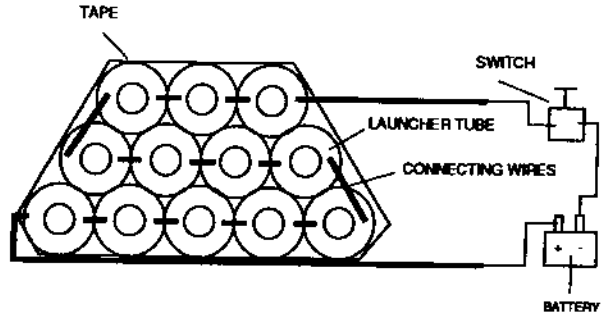


Figure 43. Rear view showing electrical connections.

Install an engine and igniter into each rocket, wrap the igniter wires around the launch rods as previously described, and load the rockets into the tubes. The igniters, via the protruding ends of the launch rods, are connected in series.

Angle-of-launch adjustment is accomplished by wedging

wooden pieces under the front of the tube assembly. A launch frame proper, incorporating a simple adjustment mechanism, can be improvised easily if required.

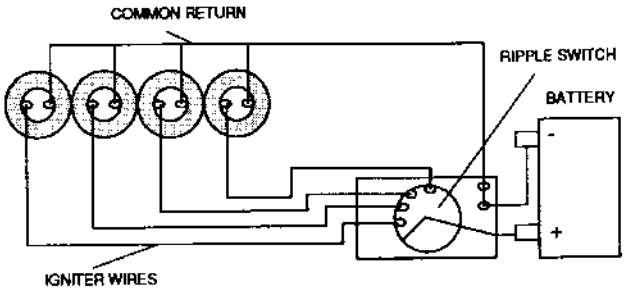


Figure 44. *Individual firing variation.*

CHAPTER 6

MISSILE PLANS

The following plans outline the construction of pad-launched, tube-launched, and tube-launched, optically tracked, radio-controlled (TORC) missile systems. These plans should fire your imagination and suggest any number of possible variations, modifications, and improvements.

GENERAL CONSTRUCTION NOTES

1. The dimensions are not absolutely critical and may be varied slightly according to available parts.

2. For maximum strength, the grain of the balsa wood should follow the leading edge of the fin.

3. The engine mount/ejection tube dimensions shown in the plan for the pad-launched missile assumes the use of two "D" suffix engines. For custom engines with a larger diameter, simply scale up the mount accordingly.

The "D" engine is fitted into the shoulder-launch missile on the friction-fit principle by wrapping it with masking tape or building up its external diameter with thin card.

4. The engine stop piece used here is 1/16 inch thick and has an external diameter that allows for a friction fit inside the engine mount tube and an internal diameter of around 1/8 inch less. It should be secured with adhesive within the engine mount tube at a point equal to the length of the engine/s to be used, less 1/4 inch. In the case of the design shown, this is 5 1/4 inch from the lower end of the body

tube. This leaves the engine (or the first of two or more engines) protruding 1/4 inch when installed and facilitates easy removal after test-firing.

5. After the initial fixing adhesive has dried, apply an extra fillet of wood glue to the fin/body joints for extra strength.

6. Being lightweight, these missiles obviously are susceptible to wind drift. Therefore, make sure you start your war on a calm day.

PAD-LAUNCHED MISSILE

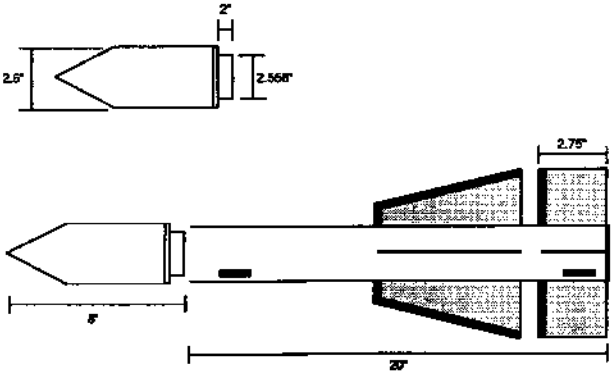


Figure 45. Major dimensions of a pad-launched missile.

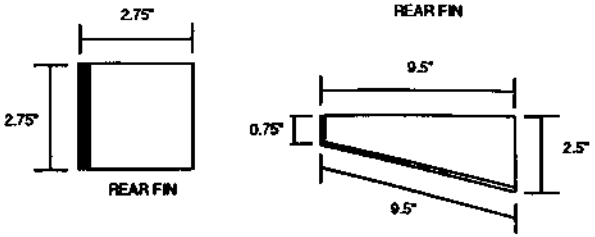


Figure 46. Fin details.

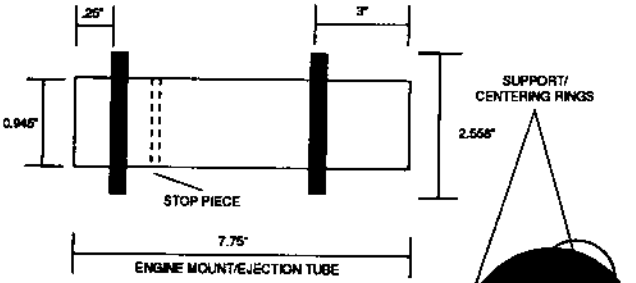


Figure 47. Engine mount details.

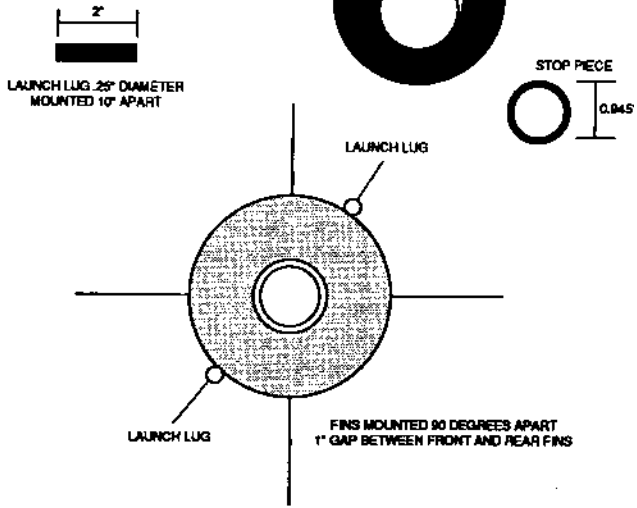


Figure 48. View from rear showing fin and launch lug positions.

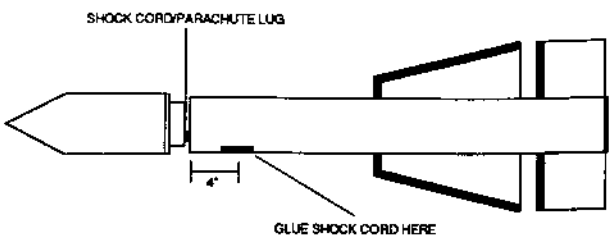


Figure 49. Shock cord attachment details.

A parachute, if required, can be improvised from a 12- to 24-inch diameter piece of polythene. Other things being equal, the larger the chute, the slower the descent.

Canopy lines can be made from six 12- to 24-inch lengths of thin cord, attached to the parachute canopy with small pieces of adhesive paper strip or circles of the type available at stationery stores.

A shock cord suitable for use with the larger missile can be made from a 24-inch length of elastic 1/4-inch wide. Simply scale it down for smaller missiles.

TUBE-LAUNCHED MISSILE

Pad-launched missiles are fun. Tube-launched missiles are really fun! Initial targets (for practice purposes) should be stationary. Trees are good, as are related objects such as sleeping members of Greenpeace. Of course, you should never fire explosive warheads at trees.

TORC MISSILE

The following is a design for a TORC (tube launched, optically tracked, radio controlled) missile. All the required nonrocket components can be obtained relatively cheaply from Radio Shack and elsewhere. A two-channel, digital proportional radio-controlled (RC) outfit and two servos are required. Try to get the type that has plug-in crystals, as this makes it easier to select channel frequencies that are less prone to interference than others.

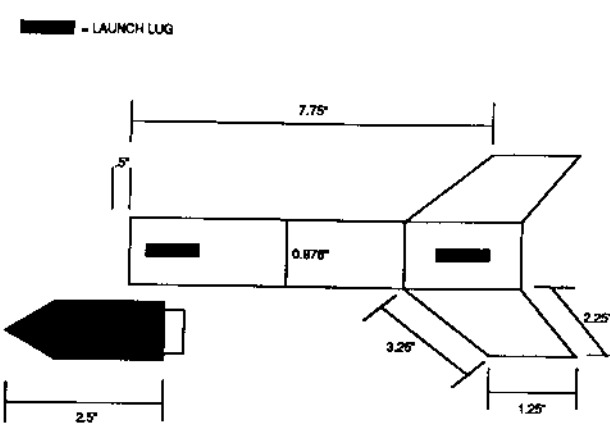


Figure 50. Major dimensions of a tube-launched missile.

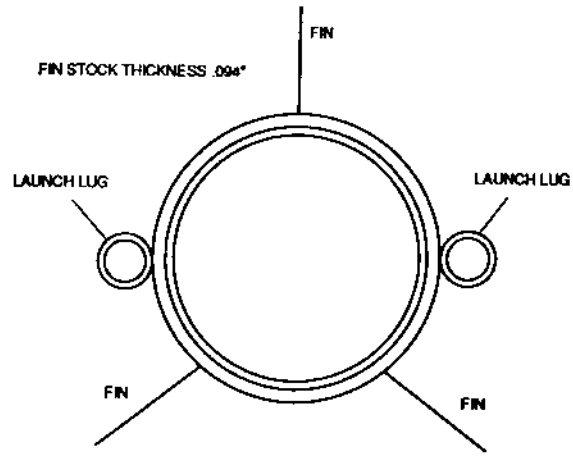


Figure 51. View from below showing fin and launch lug positions.

Typical receiver and servo sizes are 54 x 35 x 23mm and 38 x 39 x 19mm, respectively. Thus, there is no problem in installing such devices in a missile. Similarly, as the flight time of the missile will be measurable in tens of seconds, the usual radio-control battery pack need not be used. In its place, the lightest available battery or combination of batteries that will operate the system properly for, say, five minutes can be used.

Always test and get to know the flight characteristics of such a missile *before* installing any explosive materials.

The missile is based on eight D12-0 engines. These are paired to make four engines of twice the usual length using techniques already described.

Construct engine mounting tubes to suit and install, as shown in Figure 52, between two balsa wood inserts. Minimum thickness of each insert should be 1/4 inch. The drawing is not to scale but clearly indicates principle.

Insert #1 is not drilled through completely but just enough to give the engine tubes a little extra stability. Seal the tubes into both inserts with wood glue. The length of the assembly should be such that when pushed fully home, the

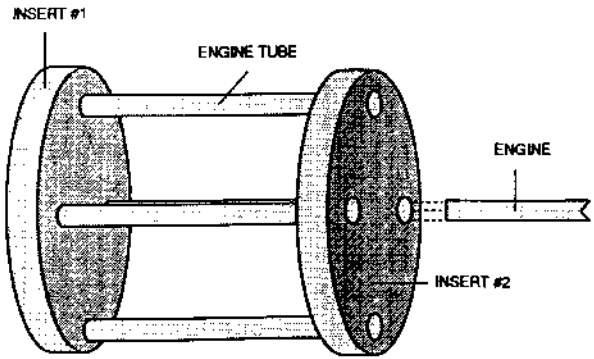


Figure 52. *Engine mount assembly.*

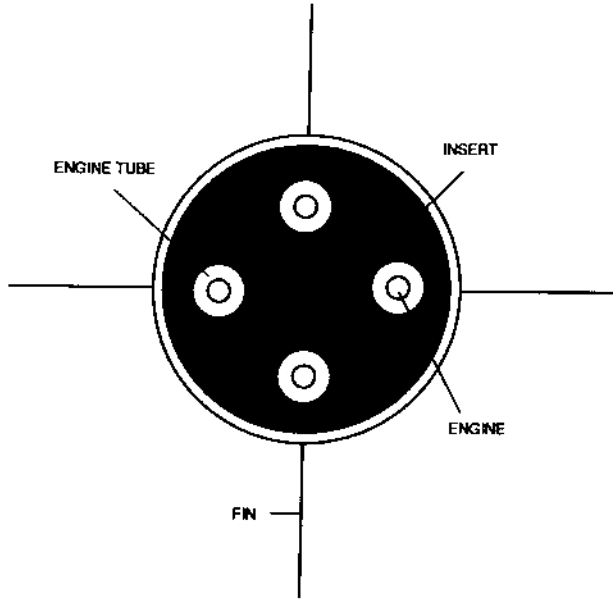


Figure 53. *Rear view of engine assembly.*

engines protrude 1/4 inch or so from the face of insert #2. The diameter of the inserts is slightly less than the internal diameter of the missile body. They, too, should be secured with wood glue.

The actuating arm of one servo connects—via a control rod and vertical link (shown in Figure 54 as HSB link)—to a horizontal hinge pin that itself is affixed to the horizontal stabilizers. Backward and forward movement at the servo end of the control rod is converted into a rotating movement of the hinge pin and, thereby, an up and down movement of the stabilizers themselves.

The other servo arm, again via a control rod, connects to a horizontal link (VSB in Figure 54), which is attached to a vertical hinge pin. This time the backward and forward

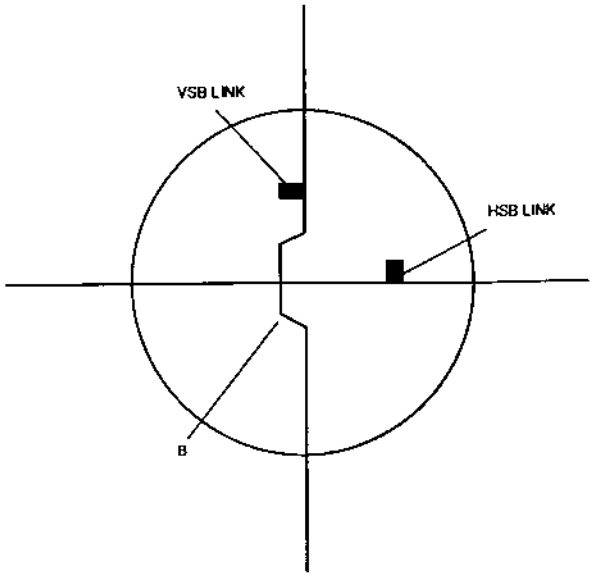


Figure 54. View from inside looking rearward of horizontal and vertical stabilizer hinges.

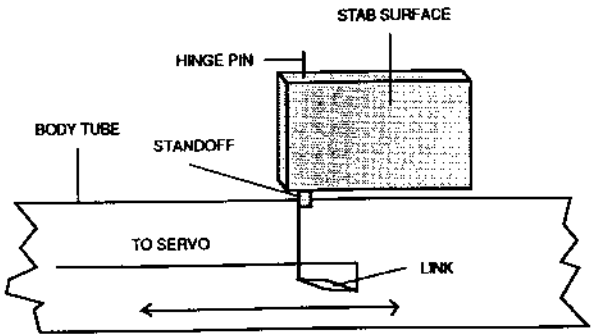


Figure 55.

movement of the servo arm is converted into a left and right movement of the vertical stabilizers. Note that the vertical hinge pin is cranked or bent slightly (B in Figure 54) for clearance purposes.

Figure 55 shows the principle a bit more clearly.

The fin and stabilizer dimensions are shown in Figure 56. There are various ways to attach the stabilizers, including mounting them on plastic or dowel hinges in a space cut from the rear of the fixed fin. In this instance, tiny retaining pieces (available from hobby shops) would be used to secure the end of each hinge. In tests, however, it was found that, probably because of the short flight time, the expedient method described here worked well enough.

Each hinge is made from 1/8-inch-diameter (approx.) wire. The wire should be of a type that allows it to be bent into a given shape, which it will then retain. The required links are commercial items available from model and hobby shops. These are attached to two lengths of the hinge wire, the servos, battery, and control rods having already been installed in the missile body. Feed the antenna through a

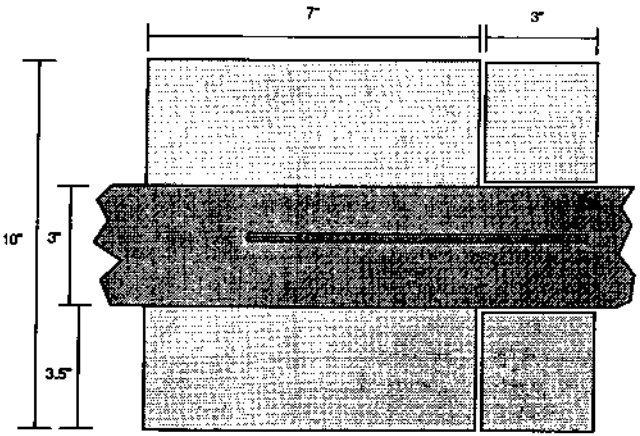


Figure 56. Fin and stabilizer detail.

small hole in the side of the missile and secure it to the body with a piece of tape.

Now pierce holes through the missile body just to the rear of the fixed fins. Install the hinge wires by poking one end of one of the wires through the missile body from the *inside*. Feed the wire through until the link prevents it from going any further and then carefully bend in the other end and push it through the opposite hole. Straighten the wire as required and hook on the appropriate linkages.

Check at this stage that the servos and linkages are working and adjust as required. If all is well, insert a small washer/bearing over each hinge end and press home into the missile body. Again, these are tiny commercial items used in model making, but any number of other things can be used. The only purpose they serve here is as a standoff for the stabilizer base—they stop the base from touching the missile body and, when the stabilizers are glued in place, limit the play in the linkage/hinge assembly.

Now either drill a hole through the front end of each stabilizer and place them onto the exposed hinge ends (securing with adhesive applied to the hinge itself), or, alternatively, gouge a small channel from the front of each stabilizer and affix them to the hinges with wood glue. Seal the hinge against the stabilizer with a length of slim dowel sliced

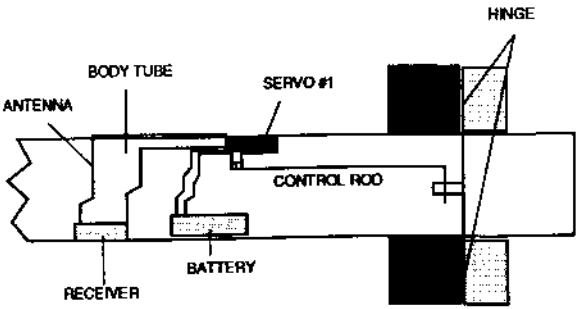


Figure 57.

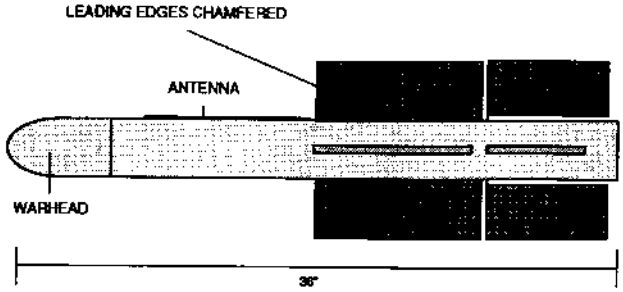


Figure 58.

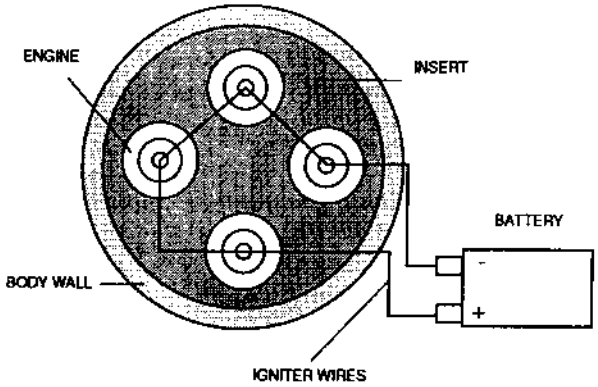


Figure 59. *Rear view of igniters connected in series (firing switch not shown).*

lengthwise and secured with wood glue.

The distance between the back of the fixed fins and the front of the stabilizers should be such that the latter can move with ease.

You will find that nowhere near the usual amount of servo movement is required to provoke a considerable reaction in the flying missile. Remember also that you won't have the decision time available to the controller of a model aircraft, for example.

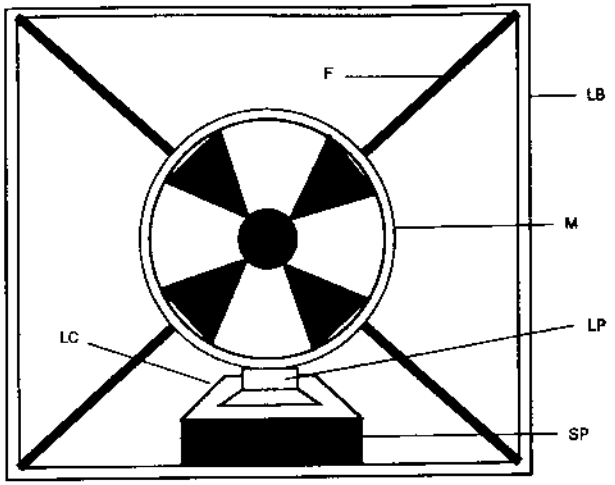


Figure 60. Front view of launcher.

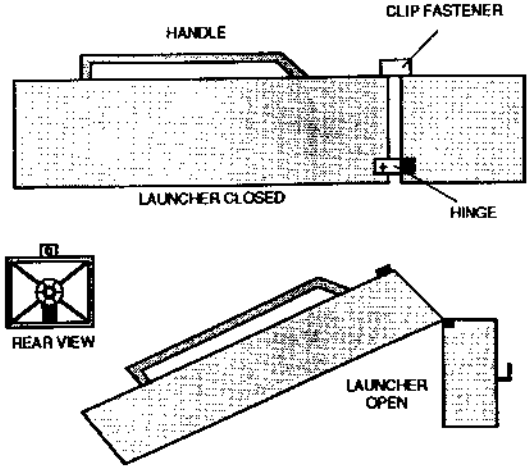


Figure 61. Completed launcher.

As this missile uses four separate engines, care must be taken that they all fire simultaneously when it is launched. Thus the ignitors should be connected in series and a high-current battery used. A motorcycle battery works well.

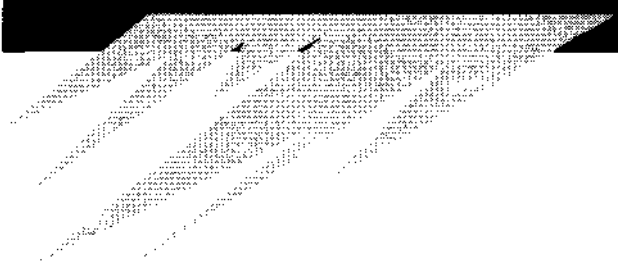
A suitable launcher is shown in Figure 60 (LB). Note that the usual launch lugs have not been used here but rather a single, sturdy launch piece (LP). This takes the form of a wooden or plastic piece, shaped as shown (slightly undersized in illustration for clarity) and attached to the missile (M) at a point close to its center of gravity. This launch piece slides into a length of track, or launch channel (LC).

The track is of such a shape as to prevent sideways movement of the missile and can be improvised easily from a length of aluminum channel. The track runs the length of the box, being secured to its floor via a support piece of wood or such (SP). The box itself should be about 6 inches longer than the missile and have a width and depth that just permits comfortable insertion of the missile fins (F).

The launcher box lid is secured with a fastener and hinged so that it will open through at least 180 degrees. In this manner, the lid forms a support and gives the launcher a minimum safe launch angle. When test-firing, it is extremely easy to overcompensate and plough the missile into the ground. Thus, an initial climb of at least 45 degrees is suggested.

Attach four narrow lengths of wood to the inside rear walls of the box to prevent the missile from falling through.

DANGEROUS ROCKET CLUB CODE



1. Construction: My missiles will be made of lightweight materials in order that they can be destroyed quickly if the police turn up.

2. Engines: I will pass on all new engine reloading information I discover to other club members.

3. Recovery: I will spend at least twelve hours recovering after a heavy night of drinking before firing explosive-filled missiles.

4. Weight limits: None.

5. Stability: If, at any time, I discover I am becoming mentally stable, I will resign.

6. Payloads: I will launch only interesting and/or dangerous payloads, but never live animals. I will kill them first.

7. Launch area: I will ensure that the launch area is free from police surveillance before firing.

8. Launcher: I understand that launching modified rockets can be dangerous. Therefore, in order to protect my eyesight, I will always get someone else to press the button.

9. Ignition system: If anyone knows how to fix the ignition system on a '67 Pontiac, please phone club HQ immediately.

10. Launch safety: I will wait until unsuspecting passersby approach before launching. In the absence of passersby, I will try to take out model aircraft or large dogs.

11. Flying conditions: I will launch modified rockets *only* when the wind is less than 10 miles per hour.

12. Prelaunch test: When conducting research activities with unproven designs, especially if explosive materials are involved, I will launch remotely, from behind cover, and in complete isolation from any persons not participating in the operation.

13. Launch angles: I will not launch dangerous rockets so that their flight path could cause them to fall on or near me.

14. Recovery hazards: If my rocket becomes entangled in a power line or other dangerous place, I will score five extra points. I will never try to recover rockets from power lines without first using a cat or other small animal to check for current. Rubber gloves and boots must be worn. If the cat won't put them on, shoot it.

Don't settle for those lame model rocket kits available from the local hobby shop. By modifying and adapting the engines and rockets, it's possible to create short- and medium-range surface-to-surface and surface-to-air missiles for some *serious* fun! Everything you need to know is here, courtesy of the Dangerous Rocket Club: principles of operation, safety precautions, and improvised warhead and missile designs, all illustrated with clear plans and schematics.

Of course, whenever dealing with explosives, rockets, and improvised modifications, failure to follow industry standards for experimentation and design may result in harm to life and limb. Therefore, this book is *for information purposes only!*

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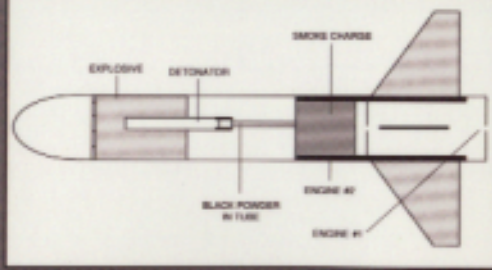

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